TEST OF VEGETABLE OIL AS FUEL IN DIRECT AND INDIRECT INJECTION DIESEL ENGINE

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PREFACE

This study was concerned with the test of vegetable oil as diesel engine fuel. The primary objectives were to evaluate, and compare the short term performance and long term durability of the direct and indirect injection diesel engine burning peanut oil, soybean oil and cottonseed oil, and their blends with diesel fuel in different proportion to that of the engine using neat diesel fuel.

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INTRODUCTION

The Problem

Finding alternative fuels for internal combustion engines has become a global problem as the supplies of oil and natural gas are approaching economic limits. Agriculture of today is dependent upon the diesel engine. Traditional sources of diesel engine fuel for agriculture have been under threat of cost escalations, quality deterioration and supply disruptions. Diesel engines running on plant and vegetable oil were demonstrated in the 1st quarter of this century. In the recent past, researchers rediscovered that diesel tractors, buses, and stationary engines can operate when fueled with sunflower, soybean, peanut, cottonseed, rapeseed, and other plant oils.

The results of a number of short-term engine tests have shown that vegetable oils are promising as an alternative fuel source for diesel engines. Pryde (1981) mentioned that long-term endurance tests show that there are serious problems in injector coking, ring sticking, gum formation and lubricating oil thickening and gelation. These problems are related to high viscosity and non-volatility of vegetable oils, which result in inadequate fuel atomization and incomplete combustion. However, it has been established that to make use of vegetable oil in diesel engines, either the engine, the fuel, or both must be modified (Seminar Report, Northern Agricultural Energy Center, Sept. 25, 1980).

Injecting fuel into the combustion chamber is the most crucial step in the operation of a diesel engine. The fuel must be forced into the combustion chamber against the pressure of the compressed air. It is also difficult to force the fuel against the compressed air in the form of a mist. If the fuel is not properly atomized, it burns slowly and unevenly - reducing the engine efficiency, raising unburned pollutants in the exhaust, and even forming deposits of solid carbon on the piston head, cylinder head, and inlet and outlet valves of the engine. Thus coking of the injector nozzles poses serious problems on startability of engines (Bruwer et al., 1980; Quick, 1980). Vegetable oil is more viscous and less easily atomized than diesel fuel and, therefore, more difficult to inject successfully. Forgiel and Varde (1981) noted that, whenever the engine was run on vegetable oil, the injector spray tip had considerable carbon build-up. Never-the-less, whether such carbon build-up will eventually alter injection characteristics and affect engine performance will require further study.

Increased fuel viscosity without injector modification interferes with needle seating, possibly causing post-injection dribbles from nozzles (Gallway and Ward, 1980). Whatever the causes, coking leads to a decline in engine power;exhaust smoke tends to increase; and eventually, multi-cylinder engines begin to misfire (Quick, 1980). If it runs too long, the engine may fail due to piston ring seizure, lubricant dilution, and other problems.

Furthermore, from the dehydration of glycerol fragments in plant oils (National Academy of Sciences (NAS)-80 Report), the potential exists for formation of acrolein during the combustion of vegetable oil in a diesel engine. Therefore, the exhaust of the diesel engine burning vegetable oil may be pungent in smell. Acrolein presence in the exhaust needs to be quantified (NAS-80 Report).

It has also been reported that modification of sunflower oil to make methyl or ethyl esters is a most promising route. The sunflower esters have viscosity and volatility properties more nearly approaching those of diesel oil compared to the original sunflower oil (Bruwer et al., 1980). However in the wrap-up of Vegetable Oil as Diesel Fuel Seminar II, 1981, it was mentioned that methyl and ethyl esters of vegetable oil mixed acids operate well in either precombustion chamber or direct injection engines; but have cloud points from -2.2 to 4.4°C which limit their climatic usefulness. Quick (1981), however, pointed out that the extra cost and high crystallization temperature are problems with esters. Hugo (1981) also reported that incomplete removal of catalyst used in transesterification process will result in severe fuel system corrosion when the ester is used in the engine. Goering et al. (1981) determined the fuel properties of eleven vegetable oils mainly produced in the U.S.A. A review of literature shows that no significant work has been done toward exploiting the possibilities of engine fuel system modification.

Now, the main problems associated with diesel engine running on vegetable oil for long term may be summarized as:

1. Difficult or no start at cold weather (sub-zero temp.).
2. Coking of injector, cylinder etc., and seizure of piston ring.
3. Clogging of fuel filters and loss of fuel supply to the engine.
4. Dilution of the engine oil and greater wear of associated engine parts.
5. Undesirable exhaust gas constituents.

It can be observed that the most important property of the test fuel related to these problems is the viscosity which is very temperature sensitive. Secondly, most of the carbon deposit may occur due to the low temperature start and post injection dribble at shut-down. Thirdly, pre-heating before combustion in the main chamber may improve combustion and emission quality.

Objectives

The general objectives of this study were, using modified fuel delivery system in two representative types of diesel engines, to burn both neat and blends of three vegetable oils (peanut, soybean and cottonseed) with diesel and to compare short term engine performance and long term durability and reliability of the test engines to those of engines burning diesel fuel. The hypotheses behind this study were:

1. Starting the engine on diesel fuel and running on test fuel and purging down to diesel before shut down would cause:

   (i) elimination of starting problem at cold weather.

   (ii) reduction of overall carbon deposit particularly at start and shut down.

   (iii) prevention of the rapid fuel-filter clogging.

2. Mixing vegetable oil with diesel fuel would reduce the viscosity and increase the combustion efficiency inside the cylinder with resulting reduction of problems and increased engine life and reliability.

The outcome of the whole test was expected to solve problems related to starting, to relate amount of carbon deposit, lubricating oil dilution, internal wear and emission quality to the test fuel types, and their properties. Thus, it might produce some definite and new information different from that obtained by earlier tests made in this field. The specific objectives were as follows:

1. To measure changes in power output, carbon deposits, and exhaust emission of diesel engine with particular attention to the injector nozzle under various load conditions using vegetable oil and diesel/vegetable oil blends as fuel.
2. To find the effects of selected fuels used in objective 1 on injector system performance such as, spray angle, output, leakage, and delay in initiation of atomization.
3. To find the effects of the selected fuels used in objective 1 on the lubrication system and the wear of different parts of the engine.

CHAPTER II

LITERATURE REVIEW

A report shows that Rudolph Diesel, the inventor of the compression ignition engine, concluded in the 1890's that any material that was injectable and that would ignite at the temperatures generated by compressing air (to 500 - 600 psi) could serve as fuel for his engine (Charles, 1923). In a 1900 demonstration, Mr. Diesel used peanut oil as fuel for his diesel engine (Peterson et al., 1981). Charles (1923) also reported that French and Belgian scientists ran diesel engines on palm oil in some of the African colonies in 1920. Professor R. J. Gutierrez of Buenos Aires, Argentina, successfully tested castor oil in a diesel engine in 1916. However, not until the energy crisis of 1974 was there serious interest into non-petroleum based alternative fuels such as vegetable oil.

During the last few years, individual researchers in the U.S., South Africa, Australia, Brazil, Canada, Thailand and Japan demonstrated that diesel tractors, buses and stationery engines can operate satisfactorily when fueled with sunflower, soybean, peanut, and rapeseed oils (National Academy of Science Report-1980). Despite the success of tests done so far, many uncertainties and potential problems are yet to be solved.

Energy Problems and Alternatives

Modern mechanized food production systems are particularly sensitive to energy shortages as was seen in the early 1970's. Petroleum prices rose dramatically, thereby increasing the farmer's cost of production, not only by the diesel fuel he was using but also through fossil fuel derived nitrogen fertilizer and pesticides. Petroleum is not regarded as a renewable resource and recent predictions have stated that the oil supply could start declining in the 1990's (Piennar et al. 1982).

In the United States, diesel fuel is playing an increasing important role for the energy needs, predominantly in the truck and rail transportation and agricultural sectors, thus producing more food and fiber per man than any other country in the world. Hofman et al. (1981) mentioned that U.S. farmers used about 3.4 billion gallons of diesel fuel in 1979 and Lipinsky et al. (1981) anticipated that by the year 2000, demand for overall diesel fuel was expected to increase 25% from the 23 billion gallons per year currently used in the United States. They also added that during the same period, the supply would be decreased by 4%. As a result, alternative renewable sources of middle distillate fuels need to be evaluated. Issacs (1982) emphasized the importance of alternate fuel research for the following reasons:

(a) US petroleum use in 1970 was equal to 1% of the country's gross national product (GNP) - in 1980, petroleum use equalled 12% of US GNP.

(b) A major oil price increase in 1985 is predicted.

(c) Some reduction in US petroleum consumption in recent years has been accomplished through importation of manufactured goods.

Calvin (1982) strongly supported the development of bio-fuel as an alternative energy source but opposed the use of coal which gives rise to "green house effect". Calvin also mentioned that due to green house effect, the average temperature on the earths surface had increased by 0.4°C in the last century with larger fluctuations at times. The higher temperature melts polar ice and increases the sea-level by 2mm annually. He also added that melted ice at the poles flows to the equator to slow the earth's rotation in milliseconds per year.

Animal fats and vegetable oils possess physical and chemical properties analogous to those of diesel fuel and, therefore, are being considered as potential energy substitutes.

The potential for growing crops on the farm which can replace all or part of the required diesel fuel promises to keep agriculture independent and can guarantee a continued food supply in the country. Peterson (1981) indicated that vegetable oils might provide all the liquid fuel needed on a typical farm by diverting 10 percent or less of the total acreage to fuel production.

Economics of Vegetable Oil as Fuel

There are many uncertainties in assessing the economic picture for vegetable oil as a diesel fuel substitute. Several economic studies indicate that plant and vegetable oils are not now economical substitutes or extenders for diesel fuel in compression ignition engines.

However, Helgeson and Schaffner (1982) reported that the relative prices of sunflower oil and diesel fuel had changed from a ratio of 4:1 in 1979 to 1.8:1 in 1981. USDA economists said, during the 1970's the price of diesel fuel rose to five times its original price at the end of

1960's; and, if the trend continues, oilseed fuels may become economically feasible (Sperry New Holland News. Vol.28. No. 2). The relative costs of diesel fuel and alternative fuels must equalize, stabilize or even favor vegetable oil fuels before it can be expected to be an acceptable fuel type. Collins et al. (1982) reported that the price of diesel fuel would have to double or triple before plant oils would become competitive on an economic basis. The Engineering Times (August, 1982) reported that a government-sponsored plant oil diversion program to meet 10% of agriculture's diesel usage would cost taxpayers over $1 billion annually. Bjornstad et al. (1982) predicted that the use of oil seeds as alternative fuel would be feasible if the relative price of petroleum fuels would increase substantially, averaging six percent over the next decade.

In Oklahoma, it seems impractical for plant oils to be completely substituted for diesel fuel in all diesel powered engines presently running when price and availability are considered. The effect on the economy from transferring a food source into a fuel source is also unknown.

The current main sources of plant oils in Oklahoma are soybeans, cottonseeds, and peanuts. As of September 1, 1981, the harvested acreage, yield and production of these plant oils in Oklahoma were (Source: Oklahoma Farm Statistics, September, 1981 Vol. 1, No. 17) as shown in Table I and Table II.

Total diesel and distillate requirement as forecasted by the Oklahoma Advisory Council will be 2047 million gallons in 1990; in 1973, it was 1598 million gallons. Assuming a linear increase, the diesel requirement in 1981 is 1800 million gallons.

TABLE I

PRODUCTION OF THREE PLANT OILS IN OKLAHOMA IN 1981

	Acreage (thousand) (Hectare)			Yield per acre (per hectare)			Production, thousand lbs. (thousand kg.)			Average Production, thousand lbs. (thousand kg.)
	1979	1980	1981	1979	1980	1981	1979	1980	1981	
Cotton	580	565	655	432	174	385(lbs.)	250,560	98,310	252,175	200,348
(lint)	(235)	(229)	(265)	(485)	(195)	(432)(kg)	(113,975)	(44,686)	(114,625)	(91,067)
Soybean	360	300	260	23	10	21(Bush)	414,000	150,000	273,000	279,000
(beans)	(146)	(121)	(105)	(57)	(25)	(52)(Bush)	(188,181)	(68,182)	(124,091)	(126,818)
Peanut	120	105	118	2200	1335	2200(lbs.)	264,000	140,175	259,600	221,258
(nuts)	(49)	(42)	(48)	(2471)	(1499)	(2471)(kg)	(120,000)	(63,716)	(118,000)	(100,572)

TABLE II

YIELD OF THREE PLANT OILS IN OKLAHOMA IN 1981

Oil Yield (by wt.)	Oil Yield, million lbs. (million kg.)	Yield, million gal. @7.7 lb/gal (million liter)
Cotton 17%	51.77* (23.53)	6.72 (25.43)
Soybeans 18.2%	50.78 (23.08)	6.59 (24.94)
Peanuts 42%	92.93 (42.24)	12.07 (45.68)
	Total	25.38 (96.05)

* 1.52 lb. of seed/lb. of cotton lint.

Considering that the power produced by vegetable oil is 95% of that of diesel fuel, the total amount of vegetable oil required in 1981 would have been 1895 million gallons. Therefore, it is not practically feasible to completely replace diesel by vegetable oil.

Even though total replacement of diesel fuel by plant oils is impractical, they could become valuable in case of an oil crisis due to war or for political reasons. Vegetable oil could be a potential diesel fuel extender or emergency fuel which can be farm produced.

Vegetable Oil vs Diesel Fuel

From the beginning of this century, internal combustion engines and petroleum fuels have evolved together. During this period, both the engines and the fuel have undergone many modifications based on a wealth of empirical data and vast practical experience. Only recently, in response to oil crisis in 1973 and subsequent fuel shortages, has a strong effort again been made on the use of reproduceable biomass fuels. Buckingham (1982) reported that it was unreasonable to expect immediate, trouble free substitution of the alternate fuels for petroleum fuels. Quick (1980) has suggested that the potential solutions for the problems that show up on endurance tests may involve either engine or fuel modification as follows:

Engine modification:

- Dual fueling
- Injection system modification--pressure
- Heated fuel lines

Fuel modification:

- Blending

- Transesterification
- Cracking/pyrolysis
- Hydrogenation to reduce polyunsaturation.

According to Buckingham (1982), engine makers are reluctant to modify engines for new fuels which are currently uneconomical and which may not become cost effective for many years. They suggest that scientists modify the new fuels for existing engines. Other researchers maintain that only with extensive engine changes will alternate fuels become viable options. Hence a compromise must be made between both ideas. Even now, though many engine experts admit that the quality of petroleum fuels reaching the nation's pumps is deteriorating and that engine changes must soon accomodate a wider range of fuel quality (Buckingham, 1982). These changes may or may not make it easier to burn plant and vegetable oil fuels. But engine makers are well aware of the problems and are seeking solutions. To find the suitability of plant oils as a diesel engine fuel, several researchers compared the chemical and fuel properties of a number of plant oils available mainly in the United States. The pioneering work has been done by Pryde (1981, 1982) and Goering et al. (1981).

Goering et al. (1981) determined the chemical properties of twelve plant oils as shown in Table III. The authors also found the fuel properties of the same plant oils, in Table IV.

Literature verifies that petroleum based diesel fuels have simpler chemical structures than vegetable oils. The former contains only carbon and hydrogen atoms which are arranged in normal (straight chain) or branched-chain structures. Liljedahl et al. (1979) pointed out that this structure is preferred for better ignition quality. Diesel fuel

TABLE III

CHEMICAL PROPERTIES OF VEGETABLE OILS*

Vegetable Oil	Fatty Acid Composition[a], % by weight											Acid[b] value	Phos.[c] PPM	Peroxide[d] value
	14:0	16:0	18:0	20:0	22:0	24:0	18:1	18:1[a]	22:1	18:2	18:3			
Castor	0	1.09	3.19	0	0	0	4.85	89.60	0	1.27	0	0.21	3.0	9.6
Corn	0	11.67	1.85	0.24	0	0	25.16	0	0	60.60	0.48	0.11	7.0	18.4
Cottonseed	0	28.33	0.89	0	0	0	13.27	0	0	57.51	0	0.07	8.0	64.8
Crambe	0	2.07	0.70	2.09	0.80	1.12	18.86	0	58.51	9.00	6.85	0.36	12.0	26.5
Linseed	0	4.92	2.41	0	0	0	19.70	0	0	18.03	54.94	0.20	6.0	33.7
Peanut	0	11.38	2.39	1.32	2.52	1.23	48.28	0	0	31.95	0.98	0.20	9.0	82.7
Rapeseed	0	3.49	0.85	0	0	0	64.40	0	0	22.30	8.23	1.14	18.0	30.2
Safflower	0	8.60	1.93	0	0	0	11.58	0	0	77.89	0	0.70	20.0	56.4
H.O. Saf-flower	0.34	5.46	1.75	0.23	0	0	79.36	0	0	12.86	0	0.26	0.42	13.6
Sesame	0	13.10	3.92	0	0	0	52.84	0	0	30.14	0	4.96	10.0	22.4
Soybean	0	11.75	3.15	0	0	0	23.26	0	0	55.53	6.31	0.20	32.0	44.5
Sunflower	0	6.08	3.26	0	0	0	16.93	0	0	73.73	0	0.15	15.0	10.7

a. Ricinoleic acid

b. Acid values are milligrams of KOH necessary to neutralize the free fatty acids in 1 gram of oil sample.

c. Phosphatide (gum) content varies in direct proportion to phosphorus value.

d. Peroxide values are milliequivalents of peroxide per 1000 grams of oil sample, which oxidize potassium idode under conditions of the test.

* Adapted from Georing et al. (1981).

TABLE IV

FUEL PROPERTIES OF VEGETABLE OILS*

Vegetable Oil	visc.[a] mm^2/s	cetane[b] No.	Hg[c] kJ/kg	Cloud point °C	Pour point °C	Flash point °C	density kg/L	water& sed. %v	carbon residue %w	Ash %w	Sulphur %w	Copper Corrosion	induction period hrs.
Castor	297	?	37274	none	-31.7	260	0.9537	trace	0.22	<0.01	0.01	1a	95.0
Corn	34.9	37.6	39500	- 1.1	-40.0	277	0.9095	trace	0.24	0.01	0.01	1a	9.3
Cottonseed	33.5	41.8	39468	1.7	-15.0	234	0.9148	0.04	0.24	0.01	0.01	1a	7.3
Crambe	53.6	44.6	40482	10.0	-12.2	274	0.9044	0.2	0.23	0.05	0.01	1a	9.0
Linseed	27.2	34.6	39307	1.7	-15.0	241	0.9236	trace	0.22	<0.01	0.01	1a	2.9
Peanut	39.6	41.8	39782	12.8	- 6.7	271	0.9026	trace	0.24	0.005	0.01	1a	6.4
Rapeseed	37.0	37.6	39709	- 3.9	-31.7	246	0.9115	trace	0.30	0.054	0.01	1a	10.0
Safflower	31.3	41.3	39519	18.3	- 6.7	260	0.9144	trace	0.25	0.006	0.01	1a	3.1
H.O. Safflower	41.2	49.1	39516	-12.2	-20.6	293	0.9021	trace	0.24	<0.001	0.02	1a	9.8
Sesame	35.5	40.2	39349	- 3.9	- 9.4	260	0.9133	trace	0.25	<0.01	0.01	1a	8.7
Soybean	32.6	37.9	39623	- 3.9	-12.2	254	0.9138	trace	0.27	<0.01	0.01	1a	7.4
Sunflower	33.9	37.1	39575	7.2	-15.0	274	0.9161	trace	0.23	<0.01	0.01	1a	5.4

a. Measured at 38 C

b. Measured using a modified form of ASTM D613 in which ignition delays were observed visually.

c. Gross heat content.

* Adapted from Goering et al. (1981).

can contain both saturated and unsaturated hydrocarbons, but the latter are not present in large enough amounts to make fuel oxidation a problem.

Vegetable oils have a more complex chemical structure as illustrated in Figure 1 (Bailey 1945 and Weiss 1970). Up to three fatty acids are linked to a glycerine molecule with ester linkages. There is variation of the fatty acids in their carbon chain length and in numbers of double bonds. Such data for some fatty acids that are commonly found in vegetable oils are shown in Table V. Some fuel properties, e.g. oxidation resistance, are markedly affected by the fatty acid composition of vegetable oils. The large size of vegetable oil molecules (typically 3 or more times larger than hydrocarbon fuel molecules) suggests that some fuel properties of vegetable oils would differ considerably from those of hydrocarbon fuels. Fuel properties of the vegetable oils are summarized in Table IV. Goering et al. (1981) found that all of the vegetable oils met ASTM limits for carbon residue, ash and, total and active sulphur.

The flash point of all of the vegetable oils is far above that of diesel fuel, reflecting the relatively nonvolatile nature of vegetable oils.

The vegetable oils are all extremely viscous with viscosities ranging from 10 to 20 times greater than No. 2 diesel fuel. Only castor oil has a viscosity more than 100 times that of No. 2 diesel fuel. The cetane ratings of most of the vegetable oils are close to or exceed the ASTM minimum of 40 for No. 2 diesel fuel. Heat contents of the vegetable oils are approximately 88% of that of No. 2 diesel.

Glycerine	+	Fatty Acids	⇒	Water	+	Triglyceride
H		O				
H − C − OH		$H - O - \overset{\|\|}{C} - (CH_2)_{16}CH_3$ (Stearic)		HOH		$H - C - O - C - (CH_2)_{16}CH_3$
		O				
H − C − OH	+	$H - O - \overset{\|\|}{C} - (CH_2)_7CH{=}CH(CH_2)_7CH_3$ (Oleic)	⇒	HOH	+	$H - C - O - C - (CH_2)_7CH{=}CH(CH_2)_7CH_3$
		O				
H − C − OH		$H - O - \overset{\|\|}{C} - (CH_2)_7CH{=}CH\,CH_2CH{=}CH(CH_2)_4CH_3$ (Linoleic)		HOH		$H - C - O - C - (CH_2)_7CH{=}CH\,CH_2CH{=}(CH)_4CH_3$
H						

Glycerine + Fatty Acids ⇒ Water + Triglyceride

Figure 1. Structural formula of a typical triglyceride and its component parts (adapted from Bailey (1945) and Weiss (1970)).

TABLE V

CHEMICAL STRUCTURE OF COMMON FATTY ACIDS*

Fatty acid	Structure[a]
Myristic	14:0
Palmitic	16:0
Stearic	18:0
Arachidic	20:0
Behenic	22:0
Lignoceric	24:0
Oleic	18:1
Ricinoleic	18:1[b]
Brucic	22:1
Linoleic	18:2
Linolenic	18:3

a. xx:y indicates xx carbons in the fatty acid chain with y double bonds.

b. Ricinoleic is the only fatty acid which contains a hydroxyl (OH) group.

* Adapted from Bruwer et al. 1981.

Most of the vegetable oils have higher cloud points and pour points than does diesel fuel. The cloud points of typical No. 2 diesel fuels range from -9 to -22°C and with a pour point range from -23 to -42°C (Steere and Marino, 1981).

There are many factors to consider in choosing a vegetable oil as a substitute for diesel fuel and fuel properties are among these factors. The fuel properties of the vegetable oil should equal or exceed those of No. 2 diesel fuel if possible. The fuel properties shown in Table IV can be used to evaluate and compare the vegetable oils. Pryde (1982) concluded that vegetable oils and their esters can not meet ASTM specifications D975 for No. 2 diesel oil for use in the diesel engine. He also added that vegetable oil modification or engine design modification may make it possible eventually for vegetable oils to become suitable alternate fuels.

From the review of literature, the advantages and disadvantages of vegetable oils for diesel fuel can be summarized as:

Advantages:

- They are liquid fuel from renewable resources.
- They would permit crop production even during a petroleum shut-off.
- They have potential for making marginal lands productive.
- Their production is less energy consuming than is alcohol production.
- They have higher energy content than alcohol.
- They have simpler technology for production at farm level.

Disadvantages:

- They are not yet economically feasible.
- Their use needs further research and development
- On-farm processing technology has not been developed yet.

Engine Modification

From the results of some earlier short term performance tests, several authors proposed and tested minor modification of engines. Quick (1980) and Pryde (1982) emphasized that engine modification might make it possible eventually for vegetable oils to become suitable alternative fuels. Quick (1980) proposed particularly the following modification as mentioned earlier:

(a) Dual fueling

(b) Injection system modification

(c) Fuel line heating

Ryan III et al. (1982) reported that heating the oil (i.e. heating the fuel line) reduced the carbon deposit problem and offered the possibility of obtaining satisfactory performance in the engine. Peterson et al. (1981) concluded that reduction of viscosity of the vegetable oils by preheating the fuel was not successful in increasing the temperature of the fuel at the injector sufficiently to be of value.

Several tests have been done with the engines having direct and indirect injection with the combination of naturally aspirated and turbocharged systems.

Bruwer et al. (1981) reported that indirect injection engine showed better performance than direct injection engine with sunflower oil as fuel. Forgiel and Varde (1981) experimented with a single cylinder air cooled naturally aspirated diesel engine and three different fuels, i.e. diesel #2, soybean oil and peanut oil. They found that operation with vegetable oils can limit maximum power output of engine but it can be increased to a baseline value by increasing nozzle orifice sizes. The authors maintained that at a small sacrifice in thermal efficiency, an engine with a nozzle having slightly larger orifice size resulted in increased smoke and unburned hydrocarbon emissions. However, the authors concluded that before modification of the injection system, a better understanding of the influence of fuel properties on mixture formation is required. The Seminar II on Vegetable Oil as Diesel Fuel (1981) at Peoria, Illinois, confirmed that all vegetable oil fuel should pass through a 3 micron final filter.

Fuel Modification

Tests of crude (no refinement after production from the mill) plant and vegetable oils as diesel fuel in USA, Brazil, South Africa, Japan, Australia and Canada, have confirmed that to obtain the equivalent performance of a diesel engine with alternate fuels as plant or vegetable oils, the alternate fuels must have some modification in chemical and physical properties (Pryde, 1981). These modifications include viscosity, pour point, cloud point, heating value, flash point, fatty acids composition and acid value. Without such modifications, major difficulties such as clogging of filter, hard start in cold weather, carbon deposit on different parts inside the cylinder, piston-seizure due to thickening of lubricating oil, crank-case oil dilution, reduction of engine efficiency and ultimate break down of the engine, may occur within a few hours of engine operation.

Consequently, the following modifications in the alternate fuels have already taken place:

(a) Initial refinement of the fuel i.e. degummed (i.e., the removal of triglycerides, free fatty acids and other fat-like minerals to prevent sticky gum-like deposits from forming in engines).

(b) Blending with diesel fuel in different proportions.

(c) Esterfication with methyl or ethyl ester.

(d) Blending with certain chemical additive.

Detailed description of the performance of the diesel engines with different combination of alternate fuels of the above mentioned modification is beyond the scope of this review, however, tests have shown some favorable and some unfavorable properties of the modified fuels.

Degummed vegetable oils have prolonged the engine running period but have not solved other problems, such as, carbon deposit inside the engine parts, clogging of the filter, hard starting at very cold temperatures, etc.

Blending the vegetable oils with certain proportions of diesel fuel (in most cases 25% or less amount of alternate fuel with the rest of diesel fuel) during short term engine performance tests, some difficulties like filter plugging, carbon deposit, crankage oil dilution have been removed substantially and, thermal efficiency, specific fuel consumption, torque and engine emission have improved. No researcher has yet made specific recommendation for use of these modified fuels for the long term durability tests of the engine. Further studies have been recommended.

The use of plant and vegetable oils blended with ethyl or methyl ester having viscosities near to that of diesel fuel in direct and indirect injection diesel engine has shown sometimes better thermal efficiency and improved engine exhaust, but their higher cloud points have limited the climatic usefulness. Quick (1980) pointed out the extra cost and high crystallization temperature problems with esters. Hugo (1981) also reported that incomplete removal of a catalyst used in the transesterification process will result in severe fuel system corrosion when the ester is used in the engine.

Plant and vegetable oils blended with certain additive have also been tested in Australia, South Africa and the United States (Pryde, 1981). Baldwin et al. (1982) studied the effect of three additives on injector deposit in a 3-cylinder diesel engine and reported that none of the additives provided an overall reduction in injector deposits but instead, resulted in greater deposits. Peterson et al. (1981) also reported that oil analysis, wear measurement and engine performance in a long term engine test with a rape oil blend with diesel indicated that the fuel additive was detrimental to the engine. He also added, however, that the additive decreased fuel filter plugging considerably. Walt and Hugo (1982) performed a test to prevent injector coking with sunflower oil by injection and fuel additives, and remarked that only a few of the many additives tested showed promise of being able to reduce coking.

Quick et al. (1982) concluded that chemical additives, claimed to reduce injector fouling when blended in diesel fuel, did not markedly improve the situation in linseed oil. The authors recommended further research.

Short Term Engine Performance with Vegetable Oils

Many reports starting from the 1st quarter of this century have described successful use of vegetable oils in diesel engines; but mostly those are the results of short term engine test and to a large extent, these results are not applicable to the present day engines that have undergone many modifications around specifications for No.2 diesel oil for greater fuel efficiency (Pryde, 1981).

Recently, short term tests of the use of vegetable oils in diesel engines have been carried out by the researchers in many countries (Pryde, 1981). Australia and Brazil as well as the United States are outstanding with a number of investigations completed and on-going. Research works with vegetable oils as diesel engine fuel are also being continued in Canada, England, Malaysia, New Zealand, Rodesia, South Africa and Japan (Pryde, 1981).

A review of literature has indicated that short term engine tests with plant or vegetable oils as diesel fuel have presented very few or no problems at all. It has been reported in the wrap-up of the vegetable oil as Diesel Fuel Seminar II at Northern Agricultural Energy Center, Peoria, Illinois, October 21 & 22, 1981 that some of the short term demonstrations seemed to have been performed more for public recognition and political gain rather than for technical advancement.

Those demonstrations were needed earlier to alert the general public to the potential of vegetable oil as a fuel for diesel engines and the need for research. However, the seminar has established several bench marks regarding the short term performances of diesel engines with plant and vegetable oils (VO) as a fuel as follows:

- All VO fuel should pass a 3 micron final filter.
- Most problems in engines resulting from use of VO are due to improper combustion.
- VO's remain a mild temperature fuel extender as no satisfactory modification for sub-freezing conditions is yet practical.
- Certain precombustion chamber engines can handle VO fuels neat or blended more satisfactorily than can direct injection engines.
- Heated fuel lines do not generally overcome the viscosity problem of VO.
- All soybean oil for fuel should be degummed and sunflower oil dewaxed (dewaxing is the process of removing crystal forming materials by filtering through 100 micron and 10 micron filters

after storing the oil at 5°C for seven days).

- Neat VO fuel should be limited to emergency fuel.

Bruwer et al. (1981) tested a total of nine different tractor models in his investigations with sunflower oil. He reported that general performance was satisfactory. Hartridge smoke values were comparable to those with diesel as fuel, knock was less audible and there were only minor differences in engine performance compared to those operated with diesel oil (Table VI). Maximum power was down 3%, brake thermal efficiencies were about equivalent, fuel consumption was up 2-3% and maximum torque was down about 6%. The authors concluded that sunflower oil compares satisfactorily with diesel oil in engine performance tests.

TABLE VI

AVERAGE[a] PERCENTAGE DIFFERENCE[b] IN PERFORMANCE TESTS COMPARED TO DIESEL FUEL*

Test	Fuel[c]	
	SN100	SN 90/10 P
Maximum power	-3.1	-3.2
Brake thermal efficiency	-0.2	+0.8
Fuel consumption	+3.6	+2.2
Maximum torque	-5.8	-5.8

[a] average of nine engines.

[b] performance with diesel fuel is taken as 100%

[c] SN100 = 100% sunflower oil.
SN 90/10 P = 90% sunflower oil + 10% petrol (gasoline)

* Adapted from Bruwer et al. 1981.

Chancellor (1981) tested diesel engines with different vegetable oils as fuel and reported the thermal efficiency as shown in Table VII.

TABLE VII

THERMAL EFFICIENCY OF SOME VEGETABLE OILS IN A DIESEL ENGINE

Fuel injected*	Indicated thermal efficiency**
Rice bran oil	43.35
Peanut oil + diesel fuel (50/50)	42.63
Soybean oil	42.51
Sunflower oil	42.44
Diesel fuel No. 2	40.66
Olive oil	39.28
Coconut oil	38.12
Peanut oil	37.92
Plam oil	35.40
Palm kernel oil	35.10

* Engine equipped with a pre-combustion chamber

** Ratio of power diverted to both friction and shaft output, to the rate of fuel energy input.

Long Term Durability Test

Short term performance tests indicated good potential for vegetable oils as diesel fuel, however, long term endurance tests have shown that a number of problems exist (Table VIII).

TABLE VIII

SUNFLOWER OIL AS DIESEL FUEL*

Problem	Cause
Fuel filter plugging	Suspended solids
Poor atomization	High viscosity
Incomplete combustion	Poor atomization, poor volatility
Coking on injector nozzles, gum formation, sticking of piston rings, crankage oil dilution	Incomplete combustion

* Source: Bruwer et al. (1981).

In USA, much of the current work is in progress at Ohio State University (Engleman et al. 1978), North Dakota State University (Hofman et al. 1981 and, Ziejewski and Kaufman, 1982), Southwest Research Institute (Fort et al. 1982 and Ryan III et al. 1982), University of Idaho (Peterson et al. 1981), University of Alabama (Adams, 1982) and at several engine manufacturers including International Harvester (Baranescu and Lusco, 1982), John Deere (Barsic and Humke, 1981), Caterpillar (McCutchen, 1981) and Perkins (Bacon et al. 1981).

Peterson et al. (1981) reported on results of short and long term engine tests using winter rape, diesel and commercial additives as the components. The study concluded that high viscosity and a tendency to polymerize within the cylinder are major physical and chemical problems. The authors were successful in running a small single cylinder diesel engine with 70% winter rape and 30% No. 1 diesel as fuel for 850 hours. No adverse wear, effect on lubricating oil or effect on power output was noted. Ziejewski and Kaufman (1982) tested a 25-75 blend of alkali refined sunflower oil and diesel fuel in the Allis-Chalmers diesel engine model 4331 as compared to a base line test on diesel fuel. The authors observed increased carbon deposit, dense fuel spray within the engine cylinders and a relative reduction of nozzle orifice diameters due to clogging.

Borgelt and Harris (1982) ran three Onan diesel engines fueled with (a) 100% diesel (b) 25% soybean oil - 75% diesel and (c) 50% soybean oil - 50% diesel fuel. The engines were operated under 50-55% load for 1000 hours. The researchers found soybean oil as a favorable fuel extender but noted that as the amount of soy oil in the fuel increased, the amount of carbon deposit inside the engine increased and recommended fuel line heating to reduce carbon deposit.

Fort and Blumberg (1982) of International Harvester tested experimental fuels made up of cotton seed oil, transesterified cotton seed oil (methyl ester) and No.2 diesel in a turbo-charged open chamber diesel engine. They ran all the tests at ambient temperature of 27°C, leaving winter operation an open issue. They concluded that although the experimental fuels were promising, much more work on these types of fuels would be required before they could be considered a commercial product.

The Vegetable Oil as Diesel Fuel - Seminar II, 1981 at Peoria, recommended in the wrap-up that basic research on VO chemistry and on the physical properties of modified VO must continue if a successful alternative to petroleum fuel were to be developed. At the same time, engine research on mechanical, dynamic and combustion factors which determine the fuel and engine system capabilities were also recommended.

CHAPTER III

MATERIALS, EQUIPMENT, AND METHODS

Diesel Engines

Two single-cylinder, naturally aspirated, air cooled diesel engines were selected for the experiment. One was a Lister LT1 (Figure 2) with direct fuel injection system and the other was a Deutz F1L511W (Figure 3) with indirect fuel injection system (i.e. pre-combustion chamber). The naturally aspirated (NA) engines were selected for test of selected vegetable oils for two reasons. First, Barsic and Humke (1981) reported that NA engine represented a large population of engines sold in agricultural and construction equipment during the last 20 years. Second, the authors also mentioned that a NA engine is more sensitive to fuel quality due to the longer ignition delays and lower performance injection equipment, typical of the selected engine design. The engine with indirect fuel injection system was selected, because Bruwer et al. (1981) tested an indirect injection diesel engine with sunflower oil for short term and found better performance of the engine compared to that of direction injection type. Moreover, the indirect injection system helps better combustion and produces less exhaust emission. Bartholomew (1981) and Quick (1980) preferred indirect injection engine to direct injection type for testing vegetable oil with higher viscosity. In this experiment, different fuel combinations were involved for testing in

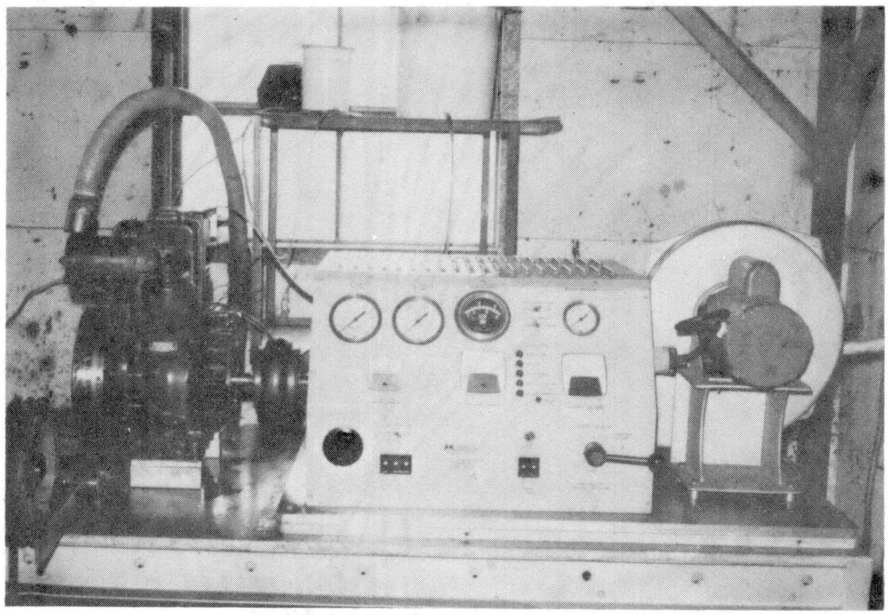


Figure 2. Lister LT1 Diesel Engine on Test Bed

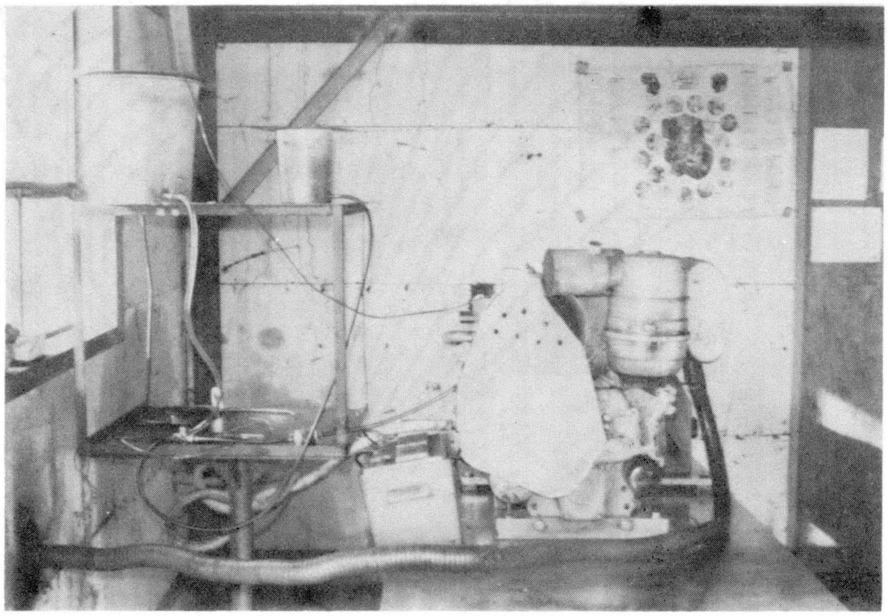


Figure 3. Deutz F1L511W Diesel Engine with Dual-Fuel System

both direct and indirect injection diesel engines for short term performance test and long term durability and reliability test.

Lister LT1

The engine specifications of Lister LT1 as supplied by the manufacturer are listed in Table IX.

TABLE IX

SPECIFICATIONS OF THE LISTER LT1 DIESEL ENGINE

Make	Lister
Type	4-cycle, vertical diesel, naturally aspirated, air cooled
No. of cylinder	one
Bore x stroke	82.55 mm x 76.20 mm (3.25 in. x 3 in.)
Displacement	0.408 liter (24.89 in.^{3})
Continuous rating output	2.98kW at 3000rpm (4.0hp at 3000 rpm)
One hour rating output	10% in excess of continuous rating at same speed
Oil pressure	70 kPa minimum at 1000 rpm
Oil pump	self-regulating plunger pump
Oil sump capacity	1.5 liters (2.64 pints)
Fuel pump	Bryce Berger
Injector	Bryce Berger, single hole, pintle type
Combustion system	direct injection
Injection pressure	15200 kPa (150 atmosphere)
Fuel consumption* (at full load subject to British standard (85) tolerance)	0.31 kg/kW.hr at 1000 and 3000 rpm 0.30 kg/kW.hr at 1500 to 2500 rpm
Fuel tank capacity	5 liters (1.1 gallons)
Dry weight	80 kg (175 lb.) approximately

* The fuel consumption figures apply to fully run-in, non-derated, bare engines without power absorbing optional accessories or transmissions.

Deutz F1L511W

The specifications of the Deutz F1L511W diesel engine are shown in Table X.

TABLE X

SPECIFICATIONS OF THE DEUTZ F1L511W DIESEL ENGINE

Make	Deutz
Model	F1L511W
Type	4-stroke, vertical air cooled diesel, naturally aspirated
No. of cylinder	one
Bore x stroke	100 mm x 105 mm (3.94 in. x 4.13 in.)
Displacement	0.825 liter (50.35 in.^{3})
Continuous rating output	8.4 kW at 2500 rpm (11.3hp at 2500rpm)
One hour rating output	10% in excess of continuous rating at same speed
Compression ratio	19:1
Oil pressure	600 kPa at rated rpm, minimum at low idling
Oil sump capacity	2.4 liters (4.22 pints)
Fuel injection pump	Bosch
Injection release pressure	11500 kPa (113.5 atmospheres)
Combustion system	two-stage combustion
Injector	Bosch, single hole, pintle type
Fuel tank capacity	15 liters (3.3 gallons)
Dry weight	116 kg (approximately)

#2 Diesel (Phillips) Reference Fuel

During the experiment, Phillips #2 diesel (#2D) was used as reference (baseline) fuel. No commercial grade fuel was used because of the possible variation of its properties. The Engine Manufacturers'

Association also recommended the use of #2 diesel (Phillips) as base line fuel for testing a diesel engine with vegetable oil. The properties of #2 diesel fuel are shown in Table XII.

Experimental Vegetable Oil

Three vegetable oils: peanut oil, soybean oil, and cottonseed oil were selected for short term performance and long term endurance tests. The selection was made on the basis of present production and future scope of increased production in Oklahoma. The selected vegetable oils are the three greatest production in Oklahoma. These vegetable oils were primarily refined (i.e. degummed) only, and not ready for human consumption. The experimental fuels were chosen from these vegetable oils either as neat or blended with different proportion in volume and as listed in Table XI. The properties of the experimental fuels are shown in Table XII.

TABLE XI

EXPERIMENTAL FUELS FOR THE DIESEL ENGINE TEST

Serial No.	Fuel/fuel blend by volume	Symbol
1	100% #2 diesel reference fuel	#2D
2	90% #2 diesel + 10% peanut oil	10P90D
3	75% #2 diesel + 25% peanut oil	25P75D
4	0% #2 diesel + 100% peanut oil	100P
5	90% #2 diesel + 10% soybean oil	10S90D
6	75% #2 diesel + 25% soybean oil	25S75D
7	0% #2 diesel + 100% soybean oil	100S
8	90% #2 diesel + 10% cottonseed	10C90D
9	75% #2 diesel + 25% cottonseed	25C75D
10	0% #2 diesel + 100% cottonseed	100C

TABLE XII

PROPERTIES OF EXPERIMENTAL FUELS

Test Fuel	Specific Gravity @15°/15°C	Viscosity at 20°C SUS[a]	Viscosity at 100°C SUS	Gross heat content Hg $\frac{kJ}{kg}$	Cloud point °C	Pour point °C	Flash point °C	Carbon residue %w	Sulphur %w	Ash %w	Acid No. mg of KOH/ml
ASTM NO.		D-445	D-445	D-240	D-2500	D-97	D-93	D-524	D-129		
#2D	0.847	38	32	45237	-18.9	-20.5	73.3	0.082	0.20	0.02	0.01
10P90D	0.855	43	32	45092	-16.7	-15.0	74.4	Negative	0.15	0.01	0.02
25P75D	0.865	52	32	44914	-12.2	-15.0	75.6	Negative	0.12	0.01	0.03
100P	0.919	377	53	44020	- 5.6	- 9.4	274.0	0.23	0.01	0.01	0.08
10S90D	0.854	42	32	45110	-18.9	-15.0	73.3	Negative	0.15	0.01	0.02
25S75D	0.866	50	32	44896	-17.8	-15.0	75.6	0.33	0.12	0.01	0.02
100S	0.924	312	51	43943	- 2.2	-12.2	279.4	0.41	0.007	0.01	0.04
10C90D	0.854	42	32	45110	-17.8	-15.0	70.0	0.011	0.14	0.01	0.03
25C75D	0.866	51	32	44896	-18.9	-15.0	73.9	0.069	0.12	0.01	0.06
100C	0.923	334	51	43957	- 5.6	- 9.4	240.5	0.40	0.006	0.01	0.13

a. SUS - Saybolt Universal Sec.

* Measurement was done by the Department of Energy, Bartlesville, Oklahoma.

Equipment and Facilities

Dynamometer

To measure engine performance (i.e torque, rpm), a Megatech Electronic dynamometer/Generator, Model DG-100, was used in the experiment. The dynamometer, equipped with the components, is shown in Figure 4. The dynamometer was precisely calibrated for determining rpm and torque developed by the engine output shaft. The machine was attached with the test engine through a flexible coupling and a clutch system which allowed the engine to warm up before being engaged with the dynamometer. The range of the dynamometer was 0-100 hp. The working principle of the dynamometer was to absorb torque, produced out of the test engine through its output shaft, by a magnetic field which produced, in turn, direct electric current. The heat produced in absorption was dissipated by air blowing from a powerful cooling fan. Water was also supplied in and out of the unit from a cold water tap. The dynamometer was equipped with an analog tachometer having a range of 0-10000 rpm with a resolution of 25 rpm. The dynamometer could be used for either clockwise or counter clockwise rotation. There were two analog type torque indicators, one to measure clockwise and the other counter clockwise torque. The torque meter could indicate a maximum torque of 100 ft-lbs (136 Nm) with the precision of a half ft-lb.

The dynamometer required connection to grounded 220 volt, 30 amp, single phase, 60 cycles electric power source using the twist lock connectors and cable provided. This also supplied power for cooling fan and generator field circuit. The system was provided with interlock circuit which would prevent it from operating if the water or air flow were

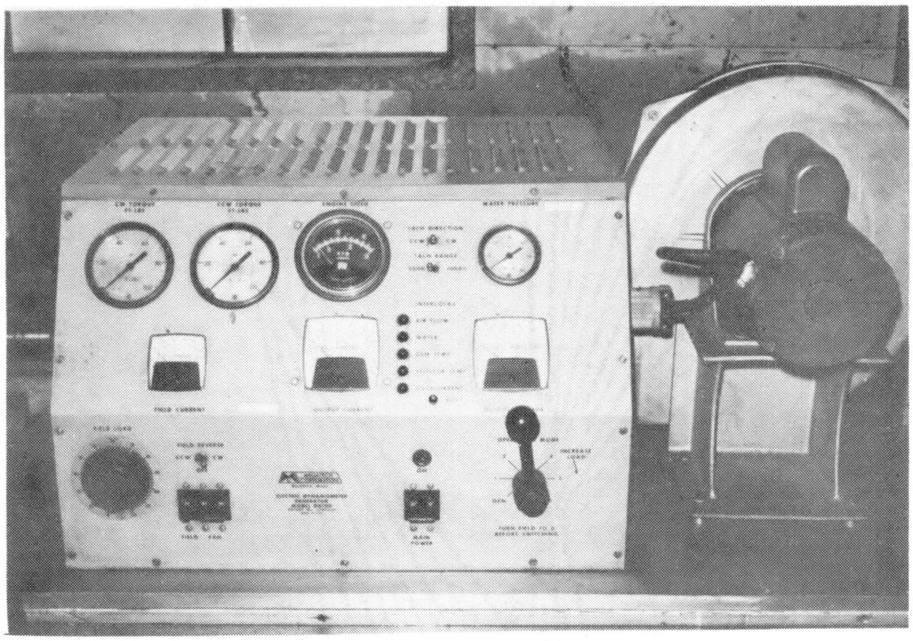


Figure 4. Dynamometer DG-100

not sufficient or absent. When one of these conditions would occur, the red light near water or air would be lit on the interlock panel.

Nozzle Tester

A Hartridge Nozzle Testmaster, Model HH601 was used in performance evaluation of the injector nozzles. Figure 5 shows a picture of the nozzle tester with the accessories. Injectors could be fixed to the tester with a quick action clamp. Through a filler gate, the reservoir of the tester was filled with experimental fuel. It was provided with a stop watch to count time in 100th of a second. The equipment was fitted with a hand lever to pump fuel through the injector nozzle, while a pressure gage indicated pressure. A control valve regulated the amount of fuel entering the high pressure pipe. The nozzle sprayed fuel inside a spray chamber fitted with a fan assembly to extract fuel mist. To test the injector, the hand lever was pressed with a slow, steady and complete stroke. At a particular pressure (opening pressure), a good nozzle should spray in the shape of a fine cone, symmetrical about the nozzle axis when viewed from all directions.

Smokemeter

To evaluate engine emission, a Bosch smokemeter was used. The smokemeter has two parts: Smoke Sampler, Model EFAW 65A and Smoke Densitometer, Model EFAW 68A (Figure 6). The smokemeter is portable, accurate and reliable testing equipment to measure the density of exhaust smoke of diesel engines. The sampling pump draws off a certain amount of emitted gas from the exhaust pipe of the respective engine and then sucks it through a paper filter disk. The paper filter disk, in turn,

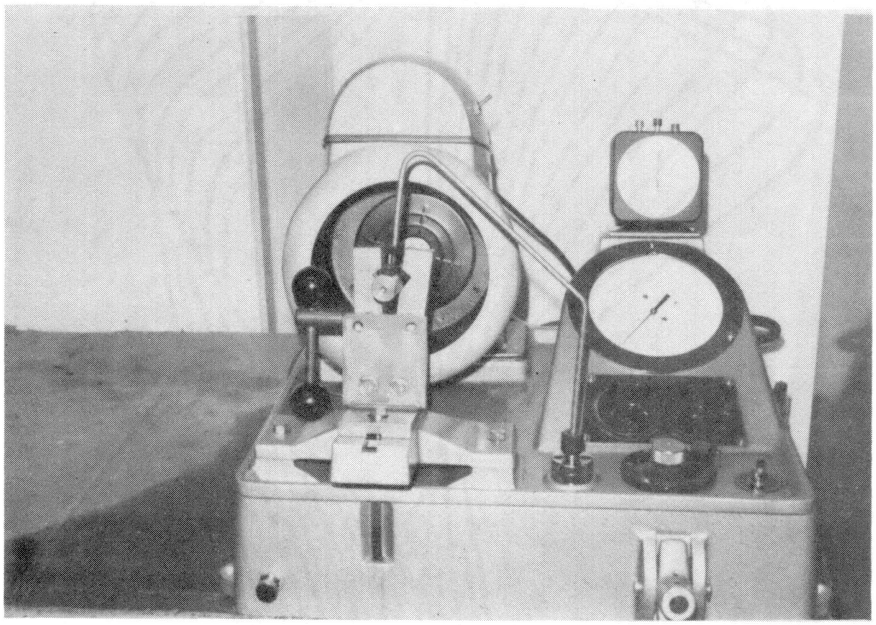


Figure 5. Hartridge Nozzle Testmaster

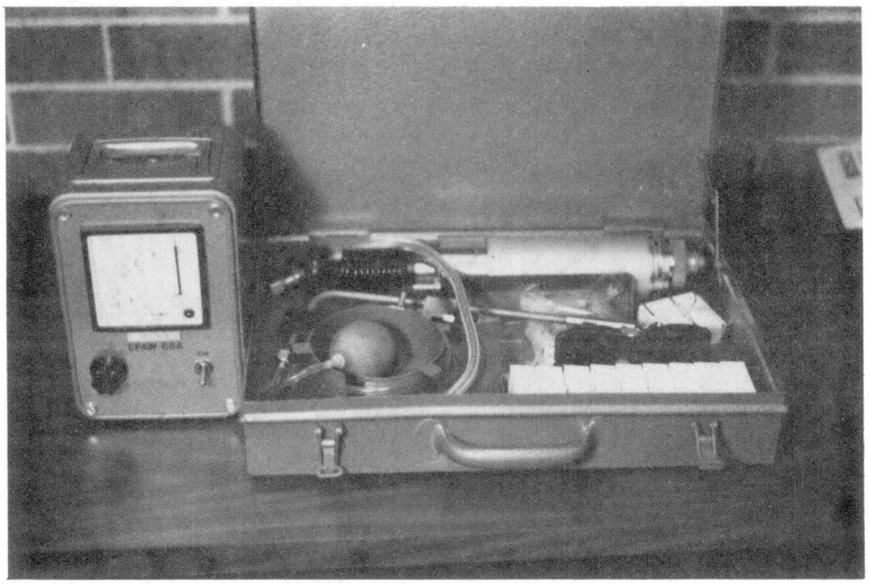


Figure 6. Smokemeter: (a) Smoke Sampler (Right), (b) Smoke Densitometer (Left)

darkens during this process and thus gives the measure of the soot content of the exhaust gases. The densitometer takes a reading off the darkened disk photo-electrically.

The densitometer is fitted with a microammeter, a potentiometer for zero adjustment and a photo-cell adapter. The photo-cell adapter has a light source which throws a beam onto the darkened paper filter disk after the adapter has been placed against the disk. The unabsorbed portion of light is then reflected from the darkened disk onto an annular photo-cell, generating a photo-cell current which is in turn indicated by the micro-ammeter. The instrument scale is divided into 0 to 10 degrees of darkening. Number 0 corresponds to an absolutely white disk, while number 10 corresponds to a disk which absorbs all the light.

Weighing and Recording System

The weighing and recording system consisted of a weighing pan with a sensor (Scientech, Inc. Model 222-003), a calculator interface (Scientech, Inc. Series 202), and a Hewlett Packard HP97 programmable printing calculator (Figure 7). The sensor can operate with electric power input and has a digital presentation of weight showing large numbers, sharply visible, reading to maximum 1999.99gm with a sensitivity of 0.01gm. Full 2kg tare is instantly available by pushing the tare button on the control. The HP97 calculator, in combination with the interface, served as a data receiver which operated directly up to six full digits of parallel Binary Coded Decimal (BCD) output of the balance. The calculator was programmed and ready to take the measurement when data entry was signalled by remote switch held at hand of the operator. When the experimental set was ready to record the weight of the fuel burned by the

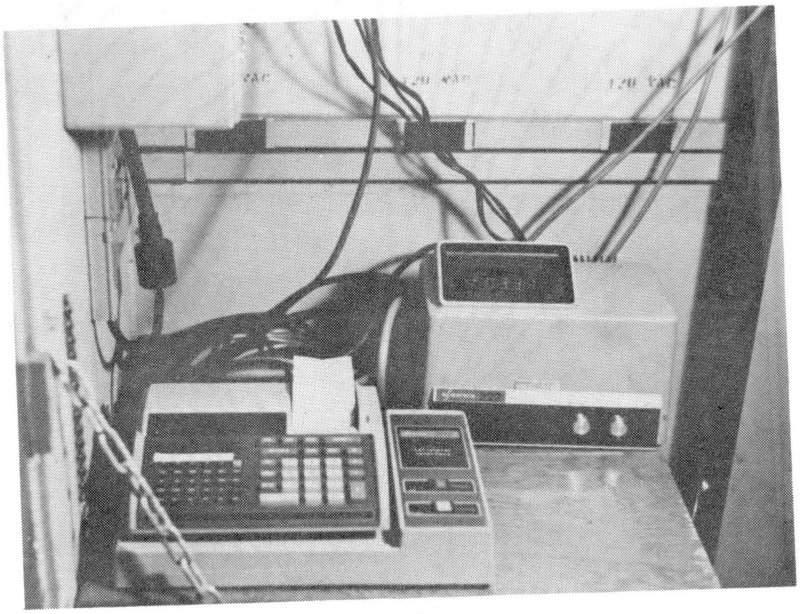


Figure 7. The Weight Recording System

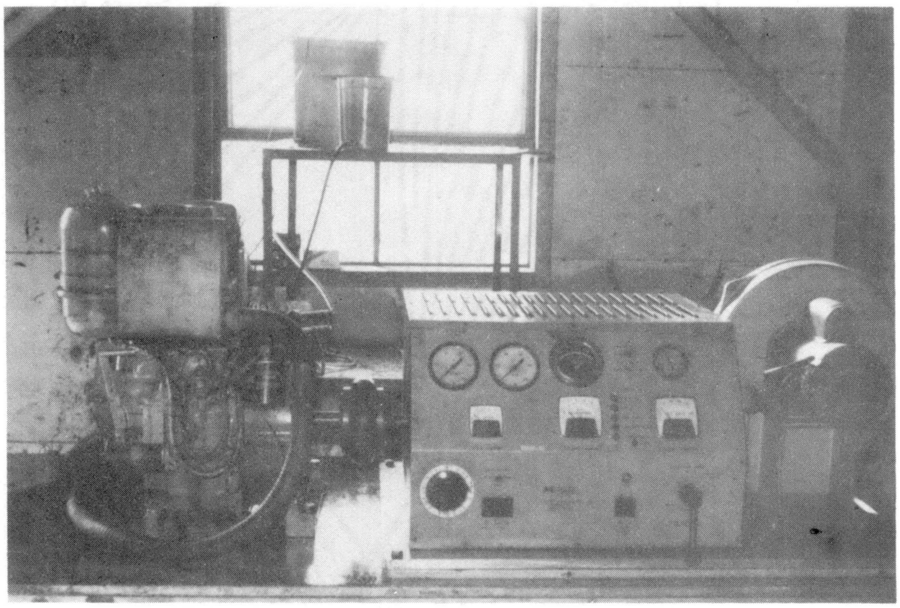


Figure 8. Test Set-up of Deutz F1L511W Diesel Engine

test engine, a stop watch and the weighing system were started at the same time. After a particular interval of time (e.g. 60 seconds), the stop watch and the weighing system were stopped at the same time. The difference between the initial and final record of the weight was the amount of fuel burned in elapsed time, recorded by the stop watch.

Other Equipment and Facilities

The experiment also needed other equipment like a double pan balance with weight-set in gms, capable of measuring up to 0.01gms. An electronic digital stopwatch, a barometer, a set of wet and dry bulb thermometers were also used at various stages of the experiment. A standard nozzle cleaning kit was used for removing carbon deposit from the engine internal parts. The whole set-up of engine and dynamometer were mounted on test bed made of steel structures fabricated in the Agricultural Engineering Laboratory. The laboratory also provided fuel measuring glass wares, camera set, calipers, gages for taking precise dimension of various engine parts. Many special tools and hardware were made in the Agricultural Engineering workshop for tearing down and assemblying the engines.

Experimental Plan and Procedures

Plan of Experiments

The experiment was planned to be done at two stages: Short term performance tests and long term endurance tests. Short term tests were conducted to determine engine power output, brake thermal efficiency, specific fuel consumption and exhaust smoke. On the other hand, long term tests were run for a period of 200 hours or more on a particular engine burning a particular fuel to observe the ability of engine to produce rated power continuously, to determine the amount of wear, carbon deposit, change in lubricating oil quality and change in exhaust emission. Considering the scope and time availability of this experiment, tests were conducted with only two diesel engines without having enough sample for a replicated statistical design.

Short Term Performance Tests

The experimental fuels are shown in Table XI for short term test for both engines. These tests included Maximum Power-Fuel Consumption and Varying Power-Fuel Consumption Test. At first, the engine was broken-in burning #2 diesel according to engine service manual. The lubricating oil was changed, the valves tappets were reset correctly. An alternate fuel delivery system was designed such that the engine was started, at first, on #2 diesel and after the engine had warmed-up, it was switched to alternate fuel, and before shut down, the engine was changed to diesel fuel again (Figure 3). A 3 micron fuel filter was connected in the fuel line during the test.

The Maximum Power-Fuel Consumption Test was conducted according to standard procedure (ASAE S209.5.2.2.1, Agricultural Engineers Yearbook, 1981-82, SAE J708 Jun 80) which is quoted in Appendix A. The Varying Power-Fuel Consumption Test was also performed according to the procedure prescribed in ASAE S209.5.2.2.2, 1981-82, SAE J708 June 80. The method is also attached at Appendix A.

During the above two series of tests, data were recorded at intervals of approximately 10 minutes, included crankshaft revolutions per minute, wet and dry bulb air temperatures, fuel consumed, and dynamometer torque. The barometric pressure was recorded at the beginning of the run and at 1 hour intervals thereafter. The duration of each test was a minimum of 2 hours' continuous operation.

Prior to testing each fuel, the injector of the engine was removed and cleaned of all carbon deposits. A new fuel filter was installed and the fuel system was flushed with diesel. The lubricating oil was checked, the tachometer and torquemeter were zeroed and checked for accuracy and recalibrated, if necessary. The engine was started at first using #2 diesel and allowed to warm up and to stabilize under rated speed and torque. The engine was then switched to alternate test fuel and run for 1-2 hours to attain stable rated speed and torque. When the dynamometer indicated a relatively stable reading (i.e. within 1% of the rated torque and speed), the observation was recorded. After each test was over, the engine was again switched to #2 diesel and run for 1-2 hours to get the fuel system washed off. The test set-up for both engines are shown in Figures 2, 3 and 8.

Long Term Endurance Tests

After completing the short term tests, three fuels: #2D, 10P90D and 10C90D were selected for long term tests on the Lister engine and five fuels: #2D, 10P90D, 10S90D, 10C90D and 25P75D for the Deutz engine. The selection was made on the basis of better specific fuel consumption/-specific power output, brake thermal efficiency, and exhaust quality. #2D was considered as a reference fuel during the long term tests. According to the recommendation of the Alternative Fuel Committee of the Engine Manufacturers' Association (The EMA report is annexed at

Appendix A), each engine was subjected to the durability screening test cycle shown in Table XIII. For each test, the operating time was a minimum of 200 hours (excluding shut downs). Before starting a test, the engine was torn down. The internal parts which might undergo wear, were measured for dimension and weight and pictures were taken. The parts around combustion chamber were pictured for determination of carbon deposit and cleaned.

TABLE XIII

TEST CYCLE FOR DURABILITY SCREENING OF ENGINES

Step	Speed	Torque	Power	Time Minutes
1	Rated	Maximum	Rated	60
2	85%	Maximum	95%	60
3	90%	28%	25%	30
4	Low idle	0	0	30
				180**

** Everyday there were to be five cycles of the above 180 minute runs equalling fifteen hours with nine hours of shut down (normal ambient temperature).

During the long term test, the baseline fuel (#2D) was tested first. The other tests were done, starting with the fuel least likely to cause engine damage followed by tests with fuels in order of increasing likelihood of engine damage (EMA Report, 1982). During the above tests, the following criteria for fuel-engine failure were observed as per recommendation of the EMA:

a) Performance: a drop in power of 5% or more that can not be corrected with minor adjustments (normal field adjustments) during 200-hour test. (Injector nozzle may be replaced to complete a test but this would constitute a failure.)

b) Durability: failure to complete 200 hours of EMA test cycle for any reason related to the test fuel only.

c) Lubricating Oil (checked daily):

   1. Viscosity: A change of 50% from new oil value.

   2. Dispersancy: Any indication of failure of dispersion.

d) Engine Life (post injection): Excessive wear that would extrapolate to a 50% or greater reduction in engine life based on the manufacuter's guidelines and experiences. Wear inspection should include, but is not limited to:

   1. Piston ring and cylinder liner wear or scuffing

   2. Bearing wear

   3. Cam and follower wear

   4. Valve guttering

During long term test, data recorded during each step of the EMA cycle included engine rpm, wet- and dry- bulb air temperatures, fuel consumption and dynamometer torque. The barometric pressure was recorded at the beginning of the run and at 1 hour intervals thereafter. After each 200-hour durability test, the engine was removed from the test bed. The engine was torn down for evaluation of wear, carbon deposit and injector performance. These operations are described briefly in a later section. The parts were then cleaned, inspected, changed if found defective. The engine was re-assembled with strict observance of the manufacturer's criteria laid down in the workshop manual. The engine was then filled with fresh oil, fixed to the test bed, run several hours for performance check. If the engine did not produce rated power, it was again torn down, causes for deficiency were removed and was remounted to the test bed. When the engine was showing rated performance, it was ready for test with another fuel.

Since there was only one dynamometer available, each of two engines was run with experimental fuel alternatively.

Injector Performance Measurement

Both test engines were supplied with single hole, pintle type injectors. The pintle nozzles were delay type with a particular feature of delivering a relatively small portion of finely atomized fuel on the first part of the needle lift because of the pintle profile, the bulk of the fuel passing through after the needle has lifted a fixed amount (Workshop Manual, Lister Diesels). The manufacturer of the engine has also mentioned that due to the above mentioned features it is not possible to completely test these nozzles in the ordinary hand pump.

In the present experiment, considering the time limitation and the scope of work, the injector performance was evaluated using the Hartridge Nozzle Testmaster, Model HH601 (Figure 5) at the existing temperature, pressure and humidity of the Agricultural Engineering Laboratory. Before and after each 200-hour test, the injector was fitted to the nozzle tester and evaluated for the following performances:

a) Leakage

b) Injection delay

c) Spray quality

d) Output

The above tests were based on the general test procedure for testing pintle nozzles (Lister, Workshop Manual) which are used in common diesel engines. The tests can be briefly described as follows:

a) Leakage: The nozzle tester was filled with test fuel up to required level. The injector was fitted to it with quick action clamp. With the pressure control valve closed and the fuel control valve opened, the hand lever was depressed rapidly several times to make the fuel lines free of air bubbles and dirt. The pressure control and fuel control valves were than opened a quarter turn each. The injector nozzle tip and body were dried with clean rag. The hand lever was then depressed uniformly at slow but constant rate and at the same time, it was observed whether any fuel leaked before the manufacturer's recommended opening pressure was reached. The observation was replicated for five times.

b) Injection delay: Following the same procedure of leakage test, it was observed whether spraying started at correct opening pressure. If it started before or after specified pressure, it was noted and corrected as per the procedure described in the workshop manual before doing the next 200-hour test.

c) Spray quality; When the nozzle tester was ready as described earlier, the fuel control and pressure control valves were opened a quarter turn each. The hand lever was then depressed uniformly at regular rate with complete stroke, the nozzle started atomizing fuel in the shape of a symmetrical cone viewed from all direction, with an even buzzing sound. Then using a Nikon F2A camera fitted with a Vivitar 90mm Macro lens, two Vivitar 283 flashes (one with auto slare), pictures of spray cones were taken with a black background.

d) Output: Following the same procedure as before, when the injector nozzle was producing a correct spray cone, the amount of fuel sprayed was captured in a graduated glass tube for a certain period of time (counted by a digital stop watch having the precision of 0.01 seconds). The glass tube was held very near to the nozzle tip so that fuel was not sprayed outside. The fuel was allowed to settle down in the glass tube for a sufficient period of time before the measurement in volume was noted.

During the above mentioned tests, the temperature, pressure and humidity of the laboratory were noted and recorded.

Smoke Sampling and Evaluation

Before and after each 200-hour test, the experiment was run with the experimental fuel for several hours till the engine was warm and attained steady conditions. Then the smoke sample was collected for the following engine operation mode as per recommendation of the EMA:

1) low idle speed, zero load
2) peak torque speed* at zero load
3) peak torque speed* at 50% load
4) peak torque speed* at 100% load
5) rated speed at zero load
6) rated speed at 50% load
7) rated speed at 100% load

* Advertised peak torque speed or 60% of rated speed; whichever is higher.

Since the engine test bed was inside the building, the smoke was directed out of the building through a short flexible pipe fitted to the exhaust pipe of the engine. By introducing the probe of the smoke sampler deep into the exhaust pipe, the exhaust gas was drawn off and sucked through a filter paper. The samples for seven engine operation modes were collected for evaluation later on. To make sure that there were no soot particles of previous tests in the sampling probe or hose which might influence the results, the hose and sampling probe were blown out with compressed air before each observation. This was checked by pumping fresh air through a filter disk which must not darkened.

The densitometer was calibrated first with the adjustment disk supplied by the manufacturer. The darkened disks were then evaluated for the Robert Bosch Smoke Number.

Lubricating Oil Analysis

During the whole experiment, Conoco Fleet SAE 30 lubricating oil was used in the engines. The oil in 5 gallon containers was procured in sufficient quantity from one lot to avoid any variation in properties. The lubricating oil samples were collected by a rubber suction pipe from the engine sump at the running temperature of the engine for 0, 60, 105 and 200 hours of the long test. The suction pipe was washed inside by a solvent and dried before and after collecting each oil sample.

Engine Wear Observation and Measurement

As per guidelines set by the EMA, the following steps were taken for observation and measurement of wear of the internal parts of the experimental engine run on experimental fuel:

a) Each 200-hour fuel test was commenced with new piston rings, valve, valve seat and guides. Other parts were in good condition. If not they were removed and replaced with new ones.

b) Dimensions and weights of all parts which might undergo wear and tear, were taken before and after each 200-hour test. The weight was taken after removal of any deposits.

c) The components of cam, crank, valves, valve guides, cylinder, piston, rings. tappets, and bearings that were likely to be affected by use of fuel, were observed, checked, and measured for proper function and specification tolerances.

d) Components of cylinder head, injector bodies, valve lifters, cam shaft and bearings were cleaned and reused if within manufacturer's specifications.

e) Parts that failed due to non-fuel related causes were replaced and test continued.

f) No engine or parts were modified during a particular fuel test series.

Carbon Deposit Collection and Measurement

After completion of each 200-hour test with an experimental fuel, the engine was torn down with great care so that the carbon deposits on engine parts, like cylinder head, piston head, piston rings, intake and exhaust valves, valve guides, injector tip were not disturbed. By using a standard cleaning kit, the carbon deposit was collected on a clean piece of paper which was weighed earlier. Then the total weight of the paper and carbon was taken on a digital balance having the precision of 0.001gm (Scientech, Inc. Model 222-003), although it was impossible to collect carbon deposit completely, visual judgement was applied to have equal cleaning of the engine parts after each test.

CHAPTER IV

RESULTS AND DISCUSSION

Short Term Performance

Maximum Power and Fuel Consumption

The preparation for maximum power and fuel consumption test was done in accordance with the procedure set in the operator's manual. The engine was, at first, warmed up for 3 hours on the dynamometer. The injector, fuel pump, and governor control settings were according to the operator's manual and remained unchanged throughout subsequent runs. The manually operated governor control lever was set to provide torque and speed for maximum power. The dynamometer load was gradually increased until the engine was operating at the rated speed specified by the manufacturer for maximum power. The corresponding fuel consumption, air temperature and barometric pressure were recorded as described earlier. The results of the maximum power and fuel consumption tests on the Lister and Deutz diesel engines with the experimental fuels are shown in Tables XIV and XV.

After completion of maximum power and fuel consumption test of the Lister engine with the fuel, 10S90D, the engine was switched to #2D. After sometime, the engine fell in speed and gradually died down. At that time, the engine ran for a total period of 15 hours only. The reason for this break-down could not be understood until the engine was

TABLE XIV

MAXIMUM POWER AND FUEL CONSUMPTION OF THE LISTER DIESEL ENGINE
WITH THE EXPERIMENTAL FUELS

Fuel Type	Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW-hour	Power Output kW-hour per kg	Temperature °C Air Wet Bulb	Air Dry Bulb	Barometer cm of Mercury
#2D	2.98	3000	0.895	0.300	3.33	15.5	21.1	74.30
10P90D	2.98	3000	0.899	0.301	3.32	15.5	18.3	74.10
25P75D	2.88	3000	0.897	0.311	3.21	20.8	22.8	73.75
100P	2.86	3000	0.978	0.342	2.92	19.4	23.05	73.81
10S90D	2.98	3000	0.973	0.326	3.07	18.3	20.0	74.00
25S75D	2.86	3000	0.956	0.334	2.99	22.2	25.0	73.77
100S	2.98	3000	1.02	0.342	2.92	13.9	17.5	74.40
10C90D	2.98	3000	0.905	0.304	3.29	20.0	23.3	74.00
25C90D	2.86	3000	0.946	0.331	3.02	16.9	18.1	73.75
100C	2.98	3000	1.02	0.342	2.92	15.5	20.0	74.30

TABLE XV

MAXIMUM POWER AND FUEL CONSUMPTION OF THE DEUTZ DIESEL ENGINE WITH THE EXPERIMENTAL FUELS

Fuel Type	Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW-hour	Power Output kW-hour per kg	Temperature °C Air Wet Bulb	Air Dry Bulb	Barometer cm of Mercery
#2D	8.43	2500	2.335	0.277	3.61	10.3	12.7	74.10
10P90D	8.39	2500	2.375	0.283	3.53	9.4	13.9	73.95
25P75D	8.28	2500	2.357	0.285	3.51	13.3	17.2	73.70
100P	8.00	2500	2.377	0.297	3.37	13.3	20.9	72.50
10S90D	8.50	2500	2.352	0.277	3.61	8.5	12.8	74.60
25S75D	8.26	2500	2.400	0.291	3.44	17.2	21.1	73.30
100S	8.24	2500	2.405	0.292	3.42	10.5	13.8	72.30
10C90D	8.47	2500	2.397	0.284	3.52	12.8	13.4	73.95
25C75D	8.36	2500	2.382	0.285	3.51	16.6	18.9	72.50
100C	8.16	2500	2.383	0.292	3.42	6.4	10.0	74.50

removed and torn down for inspection. It was found that the guide of the fuel pump tappet was broken (Figure 9). Then a new guide was installed and the engine was reassembled. When the engine was started for doing another test, it was noticed that the engine was not able to develop rated speed and torque. Later on, it was discovered that the fuel pump was not working well. Hence a new fuel pump was procured from the manufacturer and fitted to the engine. Afterwards, the engine was producing the rated speed and power without encountering any further difficulties. These break-downs were not believed to be related to the fuel used.

The results of the maximum power-fuel consumption and varying power-fuel consumption, which are shown in Tables XIV and XV were not corrected for ambient atmospheric pressure, temperature, humidity and altitude, as no standard method has been devised so far for correction of diesel engine performance when it burns vegetable oil or blends. The SAE (Society of Automative Engineers) standard conditions for expressing power output of a compression ignition engine burning diesel fuel are 76 cm (29.92 inch.) of mercury and 15.5°C (60°F) temperature at sea-level. The usual SAE method of correcting a compression ignition engine using diesel fuel is:

$$\frac{\text{Brake Power output (corrected)}}{\text{Brake Power output (observed)}} = \frac{97.9\ \text{kPa}}{P_{\text{observed}}} \times \left(\frac{\text{Temp. observed}}{302.4°\text{K}}\right)^{0.7}$$

All the tests had been performed in the pressure range of 74.30cm to 74.45cm of mercury and the temperature range of 17.5°C to 25°C. However, the effect on performance due to the variation of temperature, pressure, and humidity during the experiment, was not considered in case of all test fuels and engines. The graphical representation of the test

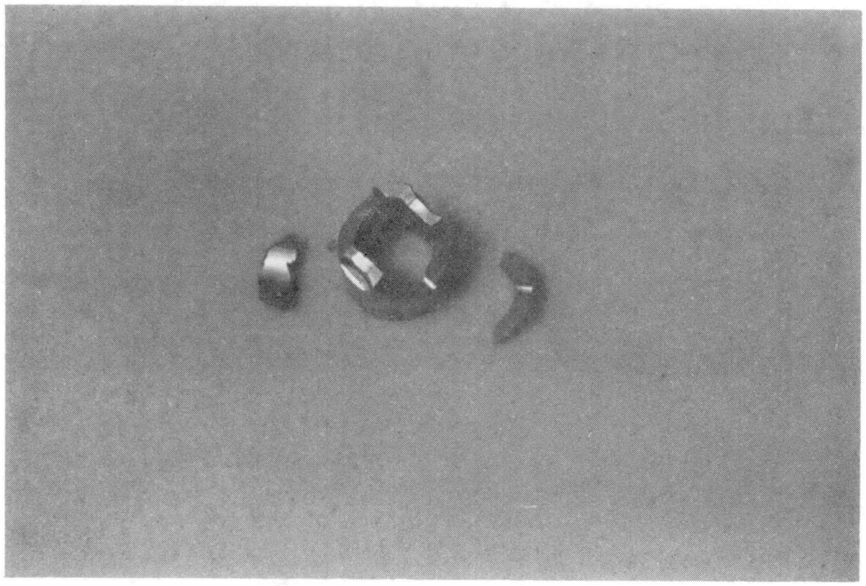


Figure 9. Broken Guide of the Fuel Pump Tappet of the Lister Engine During Maximum Power and Fuel Consumption Test

results of the Lister LT1 engine are shown in Figures 10 and 11, and that of the Deutz F1L511W engine in Figures 12 and 13. In these figures, 0% vegetable oil indicates the use of 100% diesel fuel. Between 25 and 100% vegetable oil, no test was done for the fuel and hence no comment was made regarding performance of the engines. It appears from Figure 10 that Lister diesel engine with direct fuel injection system could not develop as much brake specific power output with any alternative test fuel as it did with neat diesel fuel (#2D). As the amount of vegetable oil (by volume) increased, the brake specific power output fell in magnitude, and with neat vegetable oils it became the lowest. At 10% level of blends (i.e. 10P90D, 10S90D, and 10C90D), the engine burning peanut, cottonseed and soybean oils developed specific powers of 3.32, 3.29 and 3.07 kW.hr/kg respectively. The similar positions were also secured in case of blends of diesel with 25% volume of vegetable oils. All the neat vegetable oils developed the same amount of specific power output when they were burned in the Lister LT1 engine. The Lister diesel engine developed the same maximum power with neat soybean oil and cottonseed oil as it did with #2 diesel (Table XIV), but 4% less with peanut oil. The mixtures of 25% vegetable oils and 75% #2 diesel produced about 4% less maximum power output than did neat #2 diesel. Figure 11 represents the brake specific fuel consumption (BSFC) of the Lister engine with the experimental fuels. The BSFC was minimal (300 gm/kW.hr) for #2D fuel, and increased as the volume of vegetable oil in the fuel-mixture went up. The engine consumed the highest amount of fuel for production of one kilowatt-hour of energy when burning the neat vegetable oil as fuel.

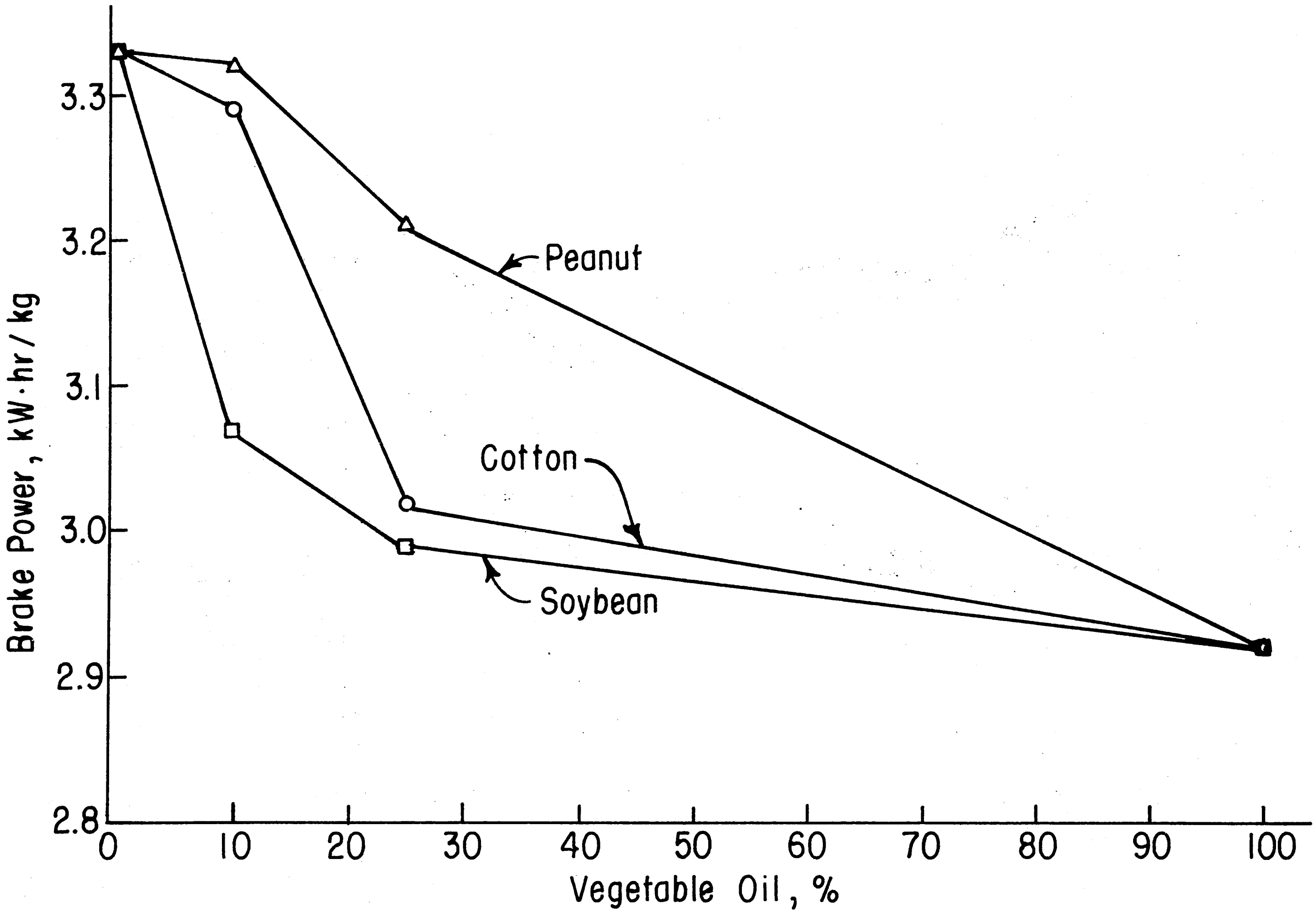


Figure 10. Effect of Increasing Vegetable Oil (by Volume) in the fuel of the Lister Diesel Engine on its Brake Power

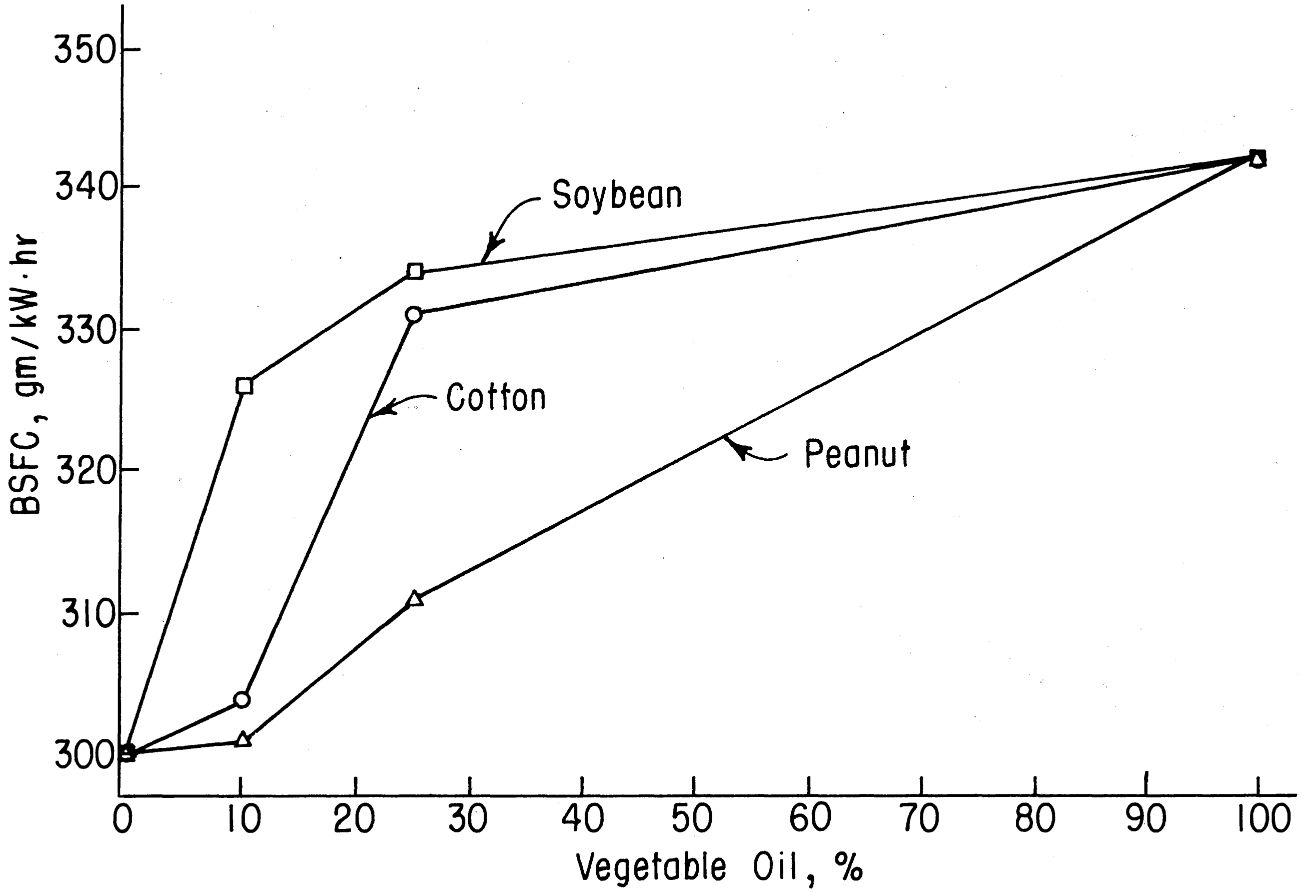


Figure 11. Effect of Increasing Vegetable Oil (by Volume) in the fuel of the Lister Diesel Engine on its Brake Specific Fuel Consumption

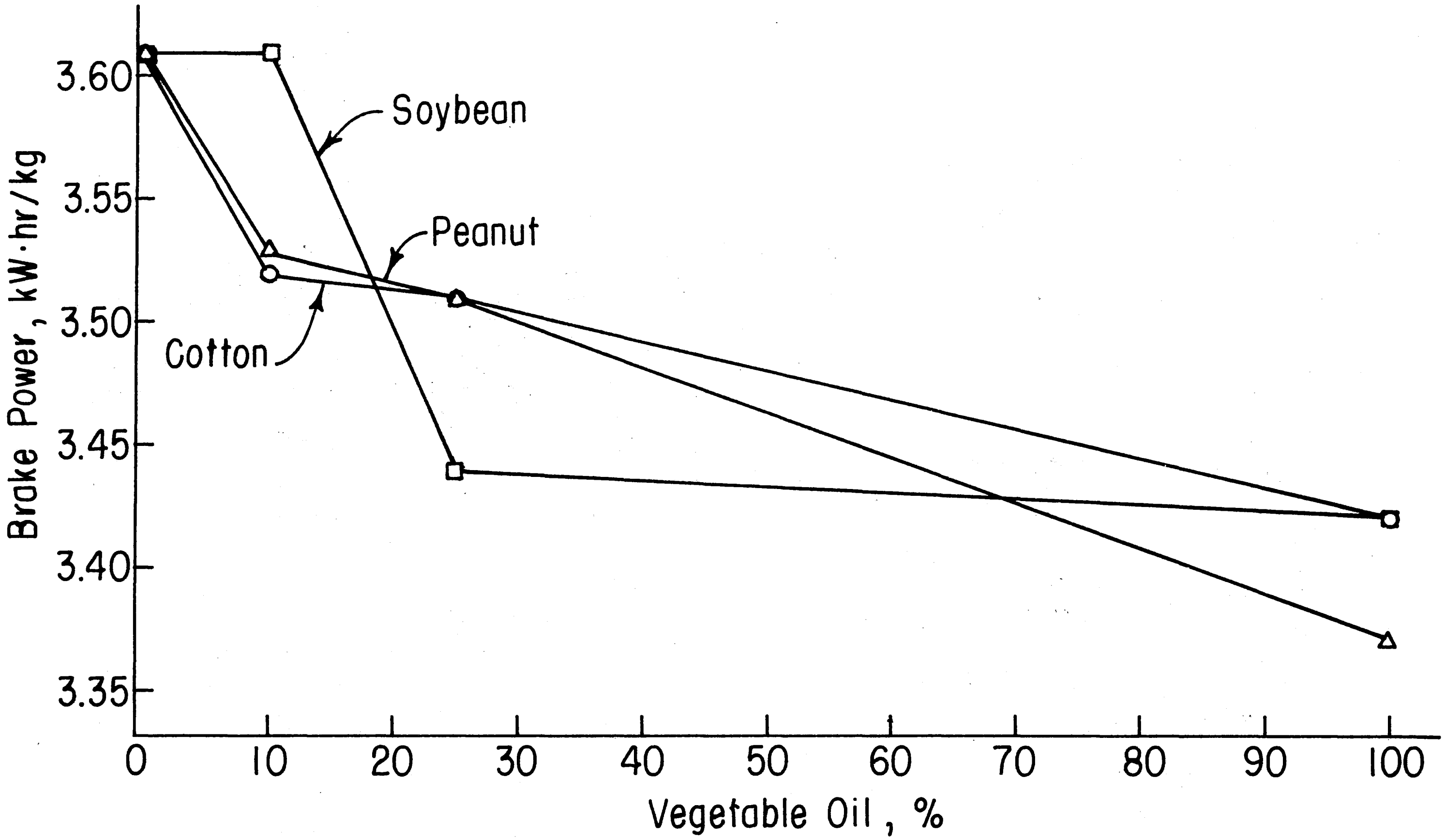


Figure 12. Effect of Increasing Vegetable Oil (by Volume) in the Fuel of the Deutz Diesel Engine on its Brake Power

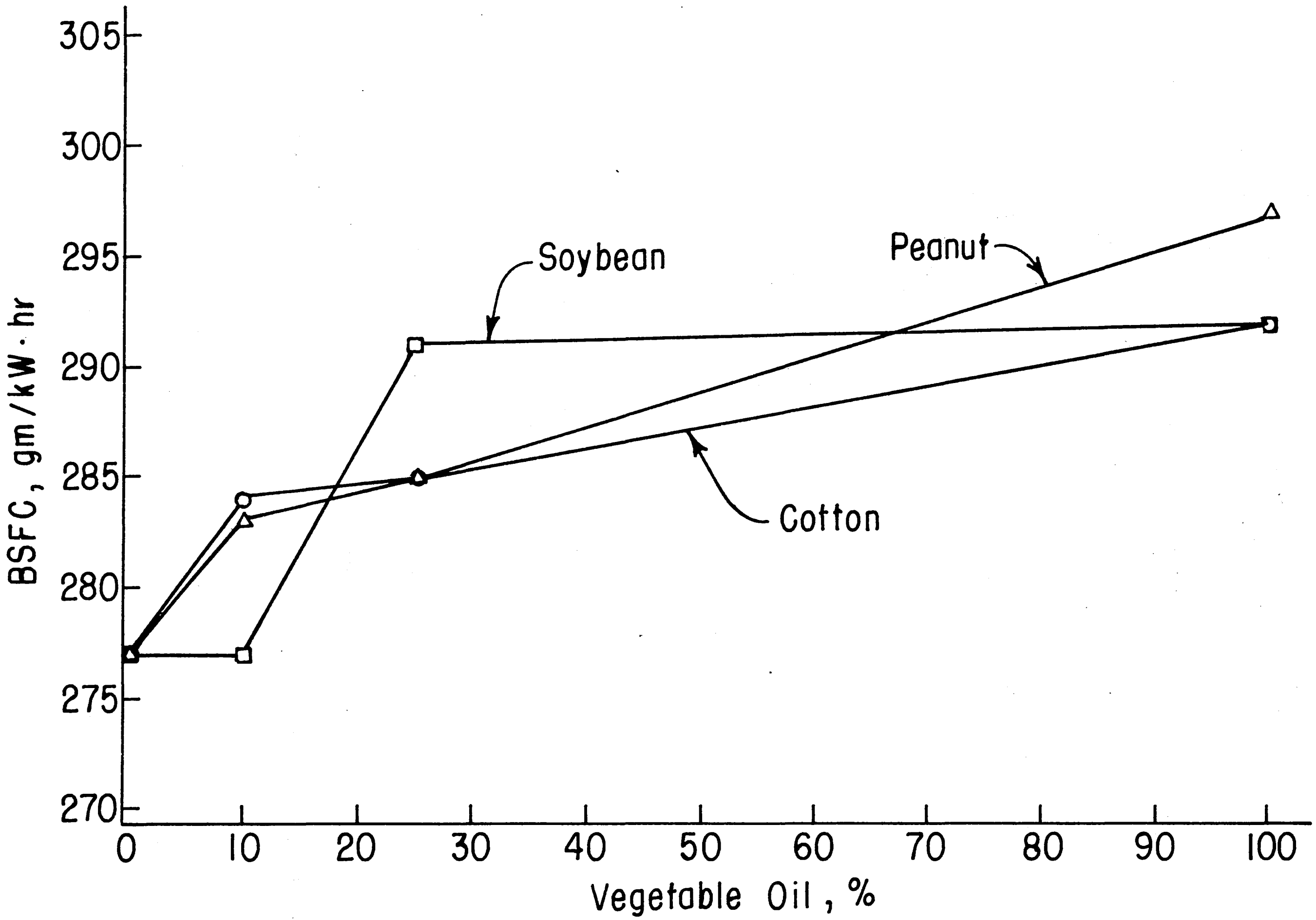


Figure 13. Effect of Increasing Vegetable Oil (by Volume) in the Fuel of the Deutz Diesel Engine on its Brake Specific Fuel Consumption

Figures 12 and 13 illustrate the specific power output and specific fuel consumption characteristics of the Deutz diesel engine with indirect fuel injection system (i.e. two-stage combustion system). The engine developed the highest brake specific power burning the fuels #2D and 10S90D. As the amount of vegetable oil in the blends increased, the specific power output fell and became minimum when neat vegetable oils were used as fuel. The engine had the least specific power output burning neat peanut oil. The blend of 10% soybean oil with 90% diesel developed 0.83% more maximum power than did diesel fuel alone (Table XV). The 25% soybean and 75% diesel fuel mixture fell sharply in maximum power output below other two mixtures (i.e. 25P75D and 25C75D) due to reasons not known. The engine with the double-stage combustion system (Deutz) always developed more specific power at output shaft than did the single-stage combustion system (Lister) indicating that indirect combustion system is better in performance with alternative vegetable oil fuels. The brake specific fuel consumption of the Deutz engine burning the experimental fuels, is shown in Figure 13. The engine burnt the least amount of #2D fuel (277 gms per kW.hr) for developing one kilowatt-hour of energy, the fuel consumption became higher with the higher amount of vegetable oil in the fuel blends. The BSFC was the highest for the neat vegetable oils, being 297 gms per kW.hr, the overall highest for the neat peanut oil.

The brake thermal efficiency for both engines are shown in Tables XVI and XVII. The results are also graphically displayed in Figures 14 and 15.

TABLE XVI

BRAKE THERMAL EFFICIENCY OF THE LISTER LT1 DIESEL ENGINE TESTED WITH THE EXPERIMENTAL FUELS

Fuel Type	Brake Thermal Efficiency (%)
#2D	26.50
10P90D	26.46
25P75D	25.72
100P	23.90
10S90D	24.44
25S75D	23.99
100S	23.93
10C90D	26.28
25C75D	24.24
100C	23.93

TABLE XVII

BRAKE THERMAL EFFICIENCY OF THE DEUTZ F1L511W DIESEL ENGINE TESTED WITH THE EXPERIMENTAL FUELS

Fuel Type	Brake Thermal Efficiency (%)
#2D	28.73
10P90D	28.20
25P75D	28.16
100P	27.52
10S90D	28.84
25S75D	27.60
100S	28.03
10C90D	28.19
25C75D	28.14
100C	28.04

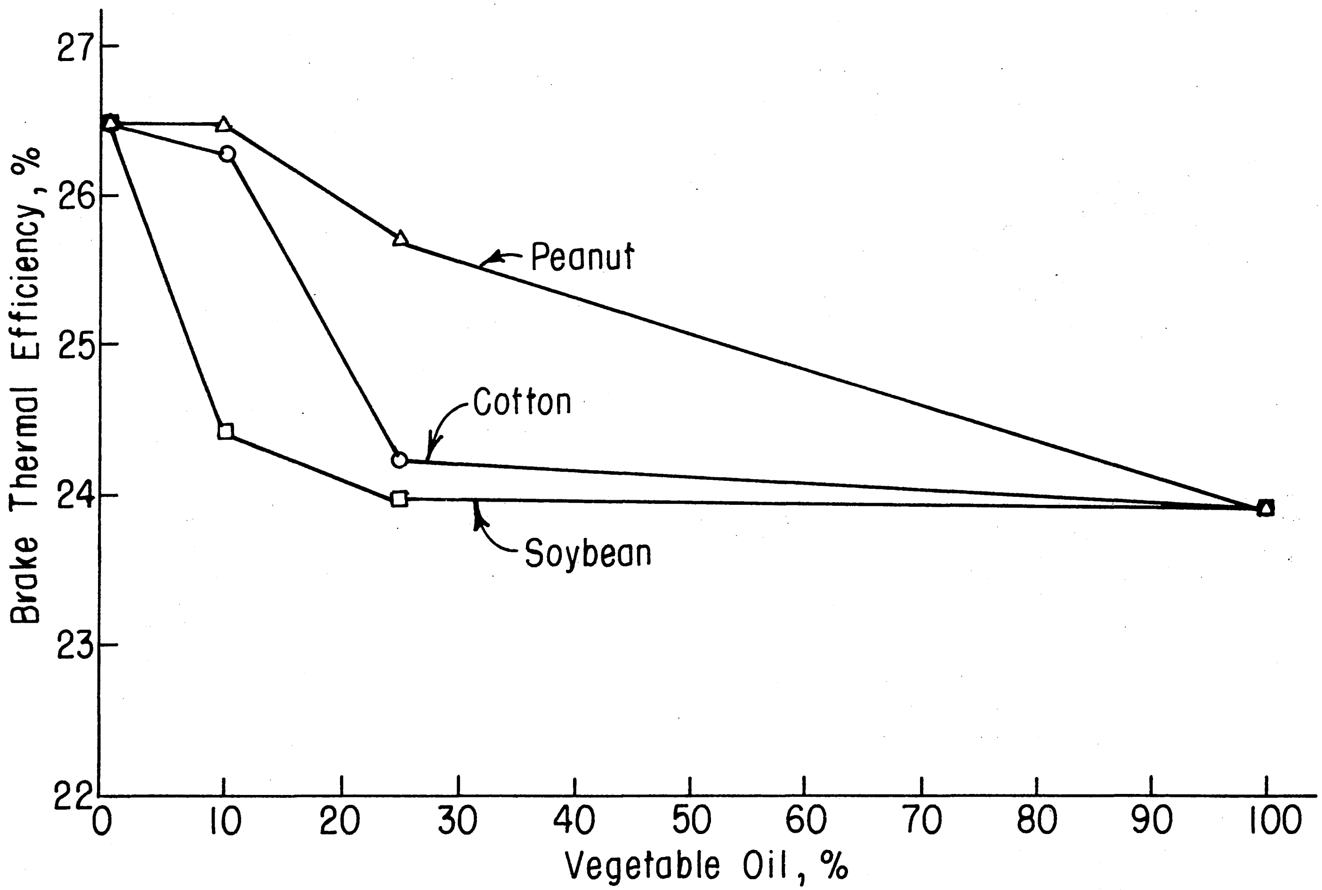


Figure 14. Effect of Increasing Vegetable Oil (by Volume) in the Fuel of the Lister Diesel Engine on its Brake Thermal Efficiency

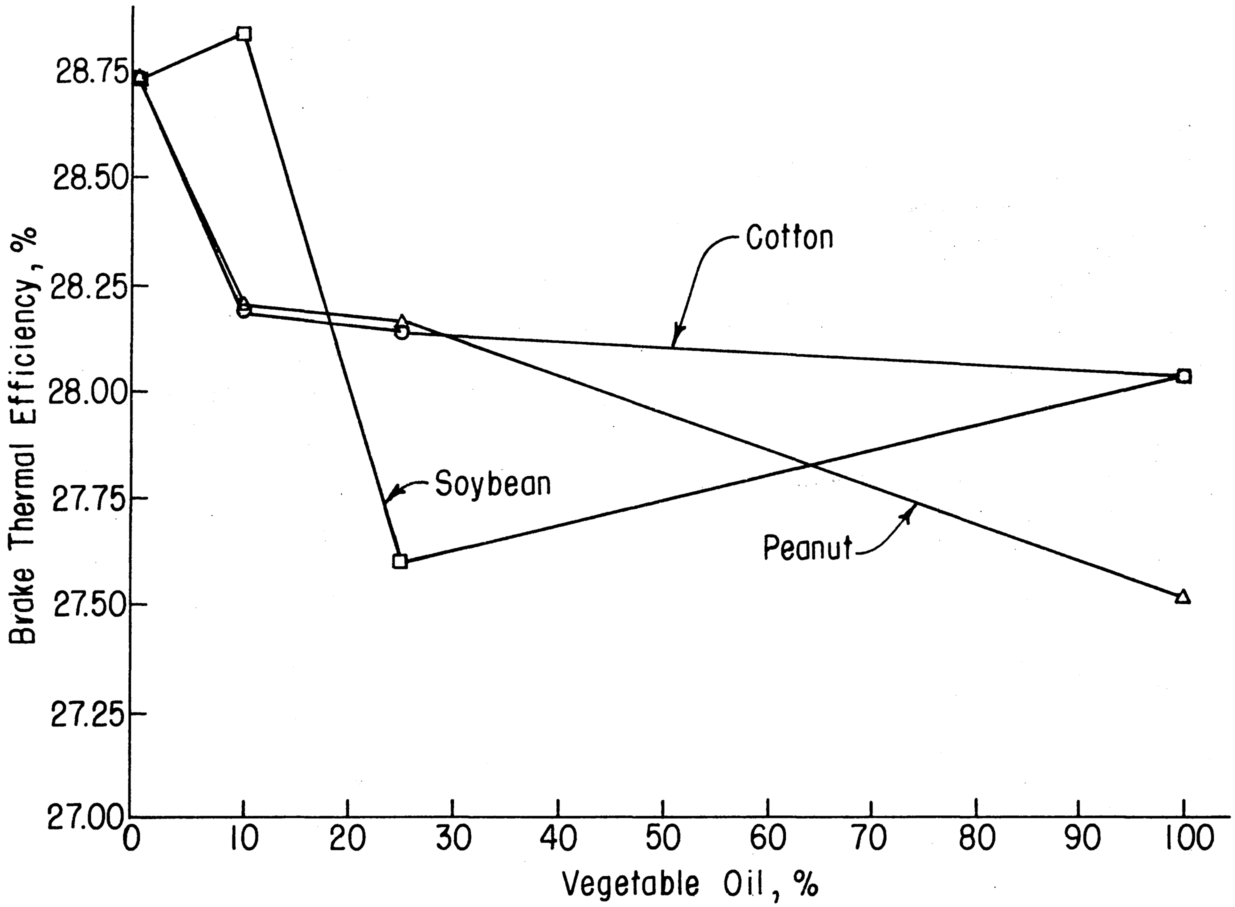


Figure 15. Effect of Increasing Vegetable Oil (by Volume) in the Fuel of the Deutz Diesel Engine on its Brake Thermal Efficiency

The brake thermal efficiency of the engines was determined as follows:

Brake Thermal Efficiency

$$= \frac{\text{Brake Power Output, kW x 100}}{\text{Mass of Fuel Consumed}\ \frac{\text{kg}}{\text{sec}}\ \text{x Gross Heat Content,}\ \frac{\text{kJ}}{\text{kg}}}$$

Example:

Break Thermal Efficiency of the Lister engine with #2D

$$= \frac{2.98 \text{ X } 100}{\frac{0.895}{60\text{X}60} \text{ X } 45237} = 26.50\%$$

Similarly, other calculations were made. The brake thermal efficiency curves (Figure 14) for the Lister engine are similar in shape to its specific power output curve (Figure 10). The efficiency of the engine burning #2D is the highest and as the amount of vegetable oil in the blend increases, the efficiency decreases, and becomes the lowest when the engine was run on neat vegetable oils. Peanut oil with the highest gross heat content burned with higher thermal efficiency then did soybean oil and cottonseed oil up to 25% of the vegetable oils with 75% of #2 diesel. Among neat vegetable oils, cottonseed oil and soybean oil were burnt with a little higher thermal efficiency than that for the peanut oil.

Figure 15 illustrates the brake thermal efficiency of the Deutz diesel engine run on diesel fuel and its blends with different proportions of vegetable oil. A mixture of 10% soybean oil with 90% diesel achieved the highest efficiency of 28.84% whereas #2 diesel had the efficiency of 28.73% when the fuels were tested in the Deutz diesel engine with indirect injection fuel system. As was the case with the Lister engine, neat peanut oil of all the experimental fuels, burned with the lowest thermal efficiency. The Deutz engine with indirect injection fuel system had higher thermal efficiency than did the Lister engine with indirect injection fuel system for all fuel combinations.

The exhaust smoke density levels expressed in Bosch Smoke Numbers for the Lister engine are summarized in Table XVIII.

TABLE XVIII

BOSCH SMOKE NUMBER OF THE LISTER ENGINE EXHAUST EMISSION BURNING THE EXPERIMENTAL FUELS

Fuel Type	Bosch Smoke Number
#2D	2.10
10P90D	2.30
25P75D	2.75
100P	3.60
10S90D	3.10
25S75D	3.45
100S	3.40
10C90D	2.80
25C75D	4.35
100C	2.45

The results are graphically expressed in Figure 16. The smaller numbers indicate the lower smoke soot density in the exhaust. The zero indicates no black soot at all and the 10 indicates completely black paper filter. As the graph illustrates, the Lister engine emitted the least dense smoke with #2D and the highest with 25C75D fuel. All neat vegetable oils developed more carbon soot in the exhaust than did neat diesel. Neat cottonseed oil produced less smoke than did neat peanut oil or soybean oil.

Data of smoke density level for the Deutz diesel engine burning the experimental fuels are shown in Table XIX.

TABLE XIX

BOSCH SMOKE NUMBER OF THE DEUTZ ENGINE EXHAUST EMISSION

Fuel Type	Bosch Smoke Number
#2D	1.0
10P90D	1.0
25P75D	1.1
100P	0.9
10S90D	1.0
25S75D	1.3
100S	0.6
10C90D	1.0
25C75D	1.2
100C	0.6

The results are also plotted in Figure 17. It appears from the graph that all neat vegetable oils produced less smoke then did neat diesel fuel. The blends of 10% vegetable oil and 90% diesel and neat diesel caused the same level of smoke density. 25% soybean oil mixed with 75% diesel made the highest amount of smoke and neat cottonseed oil and soybean oil the lowest. From Figures 16 and 17, the important characteristic of the two-stage combustion engine is shown by the fact that the Deutz engine emitted less smoke burning all experimental fuels than did the Lister engine.

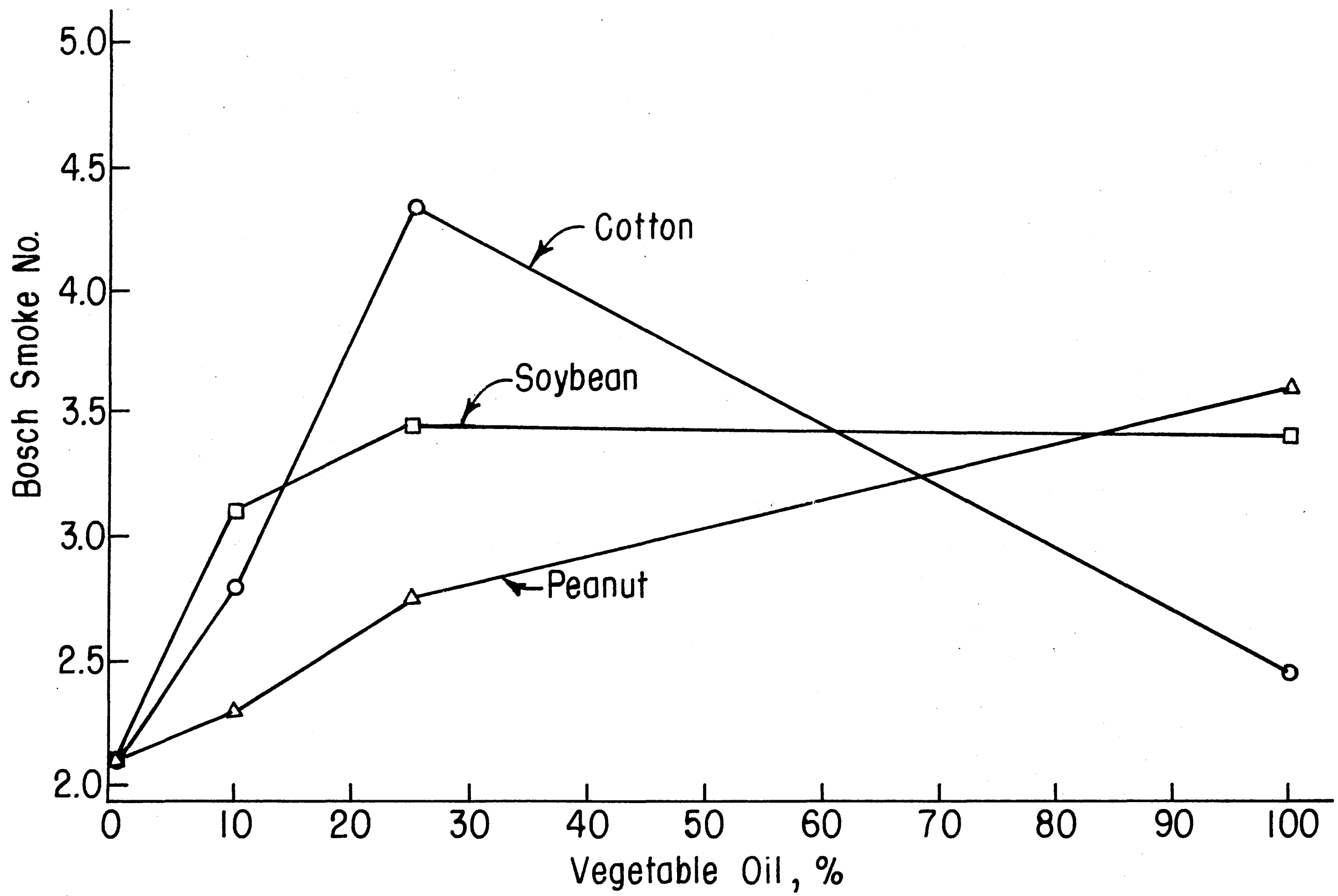


Figure 16. Effect of Increasing Vegetable Oil (by Volume) in the Fuel of the Lister Diesel Engine on its Smoke

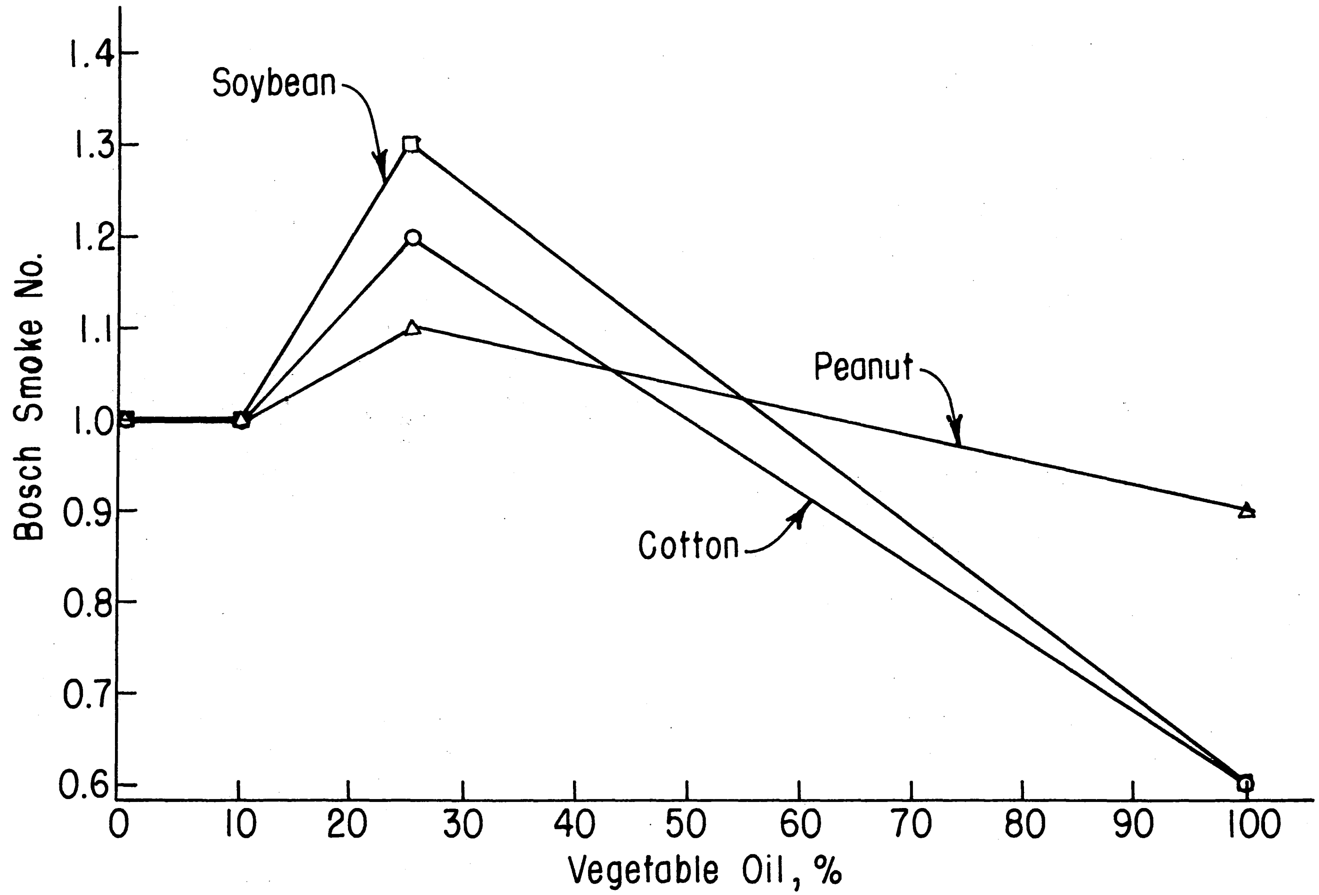


Figure 17. Effect of Increasing Vegetable Oil (by Volume) in the Fuel of the Deutz Diesel Engine on its Smoke

Varying Power and Fuel Consumption

During these tests, six different power levels were used to show corresponding fuel consumption and how the governor caused the engines to react to the changes for the dynamometer load. The power levels were: a) 85% of the dynamometer torque at maximum power, b) minimum dynamometer torque, c) 1/2 of 85% torque, d) maximum power, e) 1/4 of the 85% torque, and f) 3/4 of the 85% torque. Since an engine is generally subjected to varying loads, the average of the results in this test is a criterion for predicting the fuel consumption of the engine in general usage. The average power and fuel consumption for both engines burning experimental fuels are summarized in Table XX and XXI

From Table XX, it is evident that the Lister diesel burning #2D, developed maximum average specific power at the output shaft. Among the neat vegetable oils, soybean oil and cottonseed oil produced more power at lower fuel usage than did peanut oil. The relative performance of other fuels are similar to that done during the maximum power and fuel consumption test.

It appears from Table XXI that the fuel, 10C90D, 25C75D, and 25P75D developed more average specific power output than #2D in the Deutz engine. Cottonseed oil and its blends performed better than peanut oil, soybean oil and their blends in the varying power and fuel consumption test in respect of specific power output. The 10% cottonseed oil with 90% #2 diesel developed the maximum average brake power among all the fuels.

TABLE XX

AVERAGE POWER AND FUEL CONSUMPTION OF THE LISTER LT1 ENGINE BURNING TEST FUELS DURING VARYING POWER AND FUEL CONSUMPTION TESTS

Fuel Type	Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW-hour	Power Output kW-hour per kg	Temperature °C Air Wet Bulb	Air Dry Bulb	Barometer cm of Mercery
#2D	1.74	3433	0.814	0.468	2.14	17.2	23.3	74.00
10P90D	1.65	3300	0.780	0.473	2.11	16.0	18.3	74.10
25P75D	1.59	3367	0.830	0.522	1.92	21.7	23.9	73.75
100P	1.52	3342	0.922	0.607	1.65	20.3	24.0	73.83
10S90D	1.60	3117	0.762	0.476	2.10	18.9	21.1	74.10
25S75D	1.54	3417	0.812	0.564	1.77	22.8	26.7	73.75
100S	1.71	3375	0.915	0.535	1.87	14.6	19.0	74.40
10C90D	1.65	3250	0.802	0.486	2.06	20.3	23.8	74.10
25C75D	1.51	3334	0.846	0.560	1.78	18.9	21.5	73.80
100C	1.70	3358	0.939	0.552	1.81	15.7	20.8	74.30

TABLE XXI

AVERAGE POWER AND FUEL CONSUMPTION OF THE DEUTZ F1L511W DIESEL ENGINE TEST FUELS DURING VARYING POWER AND FUEL CONSUMPTION TEST

Fuel Type	Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW-hour	Power Output kW-hour per kg	Temperature °C Air Wet Bulb	Temperature °C Air Dry Bulb	Barometer cm of Mercery
#2D	4.79	2858	1.765	0.368	2.71	12.6	15.5	74.10
10P90D	4.78	2833	1.794	0.375	2.66	9.5	12.9	74.00
25P75D	5.00	2917	1.838	0.367	2.72	18.2	25.8	73.45
100P	4.37	2883	1.896	0.434	2.30	13.6	16.0	72.30
10S90D	4.96	2875	1.843	0.372	2.69	12.0	18.1	74.40
25S75D	4.98	2917	1.843	0.370	2.70	16.6	20.3	72.95
100S	4.69	2896	1.984	0.423	2.36	10.9	15.1	74.00
10C90D	5.16	2967	1.840	0.356	2.81	14.5	21.8	73.60
25C75D	4.98	2917	1.820	0.365	2.74	17.2	19.8	72.00
100C	4.51	2883	1.897	0.420	2.37	7.7	12.4	74.50

Selection of Fuels for Long Term Endurance Test

On the basis of specific power output, thermal efficiency, and smoke emission, measured during the maximum power and fuel consumption tests of the experimental engines with the fuels, a merit list of fuels was prepared as shown in Table XXII.

While selecting test fuels for the long term endurance tests, specific power output and brake thermal efficiency were considered more important than Bosch Smoke Number. Although neat vegetable oils emitted less dense smoke (Table XXII), because of their poor specific power outputs and thermal efficiencies, they were not selected. For higher thermal efficiency and specific power output, the fuels, #2D, 10P90D, and 10C90D were selected for the Lister LT1 engine and #2D, 10S90D, 10P90D, 10C90D, and 25P75D were selected for the Deutz F1L511W engine for long term endurance tests. The number of test-fuels was limited to 8 fuel combinations selected on the basis of their potential as viable economic fuel alternatives to diesel. As the Deutz engine exhibited higher thermal efficiency and specific power while burning alternate fuels, five fuels were selected for this engine, and three fuels were selected for the Lister engine on the same basis.

Long Term Endurance Tests

Injector Nozzle Performance

Leakage: After each 200-hour test, the injector nozzle was fitted to the nozzle testmaster and tested for pre-leakage (leakage before nozzle opening) and back-leakage as described in a previous section. The results of the leakage tests are shown in Table XXIII.

TABLE XXII*

MERIT LIST OF EXPERIMENTAL FUELS ON THE BASIS OF SPECIFIC POWER OUTPUT, THERMAL EFFICIENCY AND BOSCH SMOKE NUMBER

Specific Power Output		Br. Thermal Efficiency		Bosch Smoke Number	
Lister	Deutz	Lister	Deutz	Lister	Deutz
#2D	#2D, 10S90D	#2D	10S90D	#2D	100S, 100C
10P90D	10P90D	10P90D	#2D	10P90D	100P
10C90D	10C90D	10C90D	10P90D	100C	#2D, 10P90D, 10S90D, 10C90D
25P75D	25P75D, 25C75D	25P75D	10C90D	25P75D	25P75D
10S90D	25S75D	10S90D	25P75D	10C90D	25C75D
25C75D	100S, 100C	25C75D	25C75D	10S90D	25S75D
25S75D	100P	25S75D	100C	100S	
100C, 100S, 100P		100C, 100S	100S	25S75D	
		100P	25S75D	100P	
			100P	25C75D	

* The list is done in the descending order of performance starting the best at the top.

TABLE XXIII

BACK LEAKAGE TIME OF INJECTOR NOZZLE AFTER EACH 200-HOUR TEST

Engine Type	Fuel Type	Pre-leakage	Back leakage Time, Seconds Average	Standard Deviation
Lister LT1	#2D	no	27.73	1.34
	10P90D	no	31.58	2.45
	10C90D	no	31.19	1.74
Deutz F1L511W	#2D	no	34.03	2.12
	10P90D	no	34.50	2.70
	10S90D	no	35.33	11.88
	10C90D	no	32.91	2.70
	25P90D	no	34.00	1.71

No leakage of fuel before nozzle opening was observed during all the tests. The standard back-leakage time for the type of nozzles used in the experiment should be between the range of 6 to 55 seconds (Workshop Manual of the Lister and Deutz engine). The back-leakage time for the Lister nozzle was measured for the fall of pressure from 15.0 to 10.0 MPa and that for the Deutz nozzle was measured for the fall from 10.0 MPa to 7.5 MPa of pressure. The results of the test in Table XXIII indicate that the nozzle performance was not adversely effected by any 200-hour test with experimental fuels.

Injection delay: After each 200-hour test, the injector nozzle was tested for correct opening pressure. Data for this test are shown in Table XXIV.

TABLE XXIV

INJECTOR NOZZLE OPENING PRESSURE AFTER EACH 200-HOUR TEST

Engine Type	Fuel Type	Nozzle Opening Pressure, MPa
Lister LT1	#2D	15.5
	10P90D	15.5
	10C90D	15.5
Deutz F1L511W	#2D	11.5
	10P90D	11.5
	10S90D	11.5
	10C90D	11.5
	25P75D	11.5

For the Lister engine, the recommended nozzle opening pressure was 15.0 MPa. The opening pressure for the nozzle was set at 15.5 MPa, a little higher than normal value because of the possible fall in pressure during the long running of the engine (Lister Workshop Manual). The nozzle opened at 15.5 MPa of pressure when tested with three fuels indicating no drop in opening pressure during 200-hour tests. The nozzle of the Deutz engine opened at correct pressure in each test, indicating no fault of the injector nozzle due to use of any experimental fuel for 200-hour endurance test.

Output: According to the procedure described in the operators' manual, the injector nozzles were tested for output when they were making a correct spray cone pattern. The results of nozzle output tests are shown in Table XXV. The nozzle of the Lister engine sprayed a lesser amount of blended fuel than it did with #2D. The higher viscosities of the blended fuels might cause this difference. The nozzle output decreased gradually with hours of use indicating the possibility of carbon build-up around nozzle orifice tips. The nozzle of the Deutz engine had a similar average output for all experimental fuels except 10P90D. During 200-hour tests, no fault of the nozzles were encountered.

TABLE XXV

NOZZLE OUTPUT WITH THE EXPERIMENTAL FUELS AFTER EACH 200-HOUR TEST

Engine Type	Fuel Type	Amount ml/sec. Average	Standard Deviation
Lister LT1	#2D	0.44	0.080
	10P90D	0.36	0.110
	10C90D	0.24	0.030
Deutz F1L511W	#2D	0.17	0.009
	10P90D	0.24	0.040
	10S90D	0.16	0.020
	10C90D	0.13	0.005
	25P75D	0.16	0.011

Spray cone: After each 200-hour endurance test, the injector nozzle was tested for perfectness of spraying. The spray should normally be a perfect cone around the nozzle tip viewed from all sides. Sometimes, due to carbon build-up in the hole or at the tip, the spray shape may not be a cone. After each 200-hour test, the injector nozzle was fitted to the nozzle testmaster and according to the procedure set in the operator's manual, the fuel was sprayed from the nozzle. The pictures of the spray cones were taken by a high speed camera and flash system. The Figures 18-25 show the pictures of spray cones made by different nozzles with different fuels.

As the Figures 18-20 indicate, the spray cones made by the Lister injector nozzle were symmetrical around the nozzle tip axis in case of all fuels. The injection performance is determined by penetration distance, penetration rate, and cone angle of the spray (Ryan III, 1983). The penetration distance and the spray cone angle are complementary to each other for perfect fuel distribution in the chamber. There should be an optimum cone angle having a particular penetration distance for exposing maximum surface area of the fuel to the oxygen of air for the most efficient combustion. The pictures in the Figures 18-19, indicate similar cone pattern and penetration distance. In Figure 20, the fuel mist is more dispersed towards the bottom possibly due to taking pictures at the moment when some fuel droplets were falling due to gravity. The Figures 21-25 represent the pattern of the spray cones made by the Deutz injector nozzle using different fuels. The spray cones are less dense in these pictures than those in the Figures 18-20, showing less amount of fuel sprayed (Table XXV) by the nozzle in these cases. The spray cones look symmetrical around the nozzle tip axis except a little more dispersion of mist towards the bottom (Figures 22-24) due to gravity.

During the series of 200-hour test of both engines, no failure of engine performance was encountered due to reasons related to injector nozzle spray. No difference in nozzle performance in respect of spray cone formation due to use of #2D and alternate fuels was observed to be present during the test of both engines.

Exhaust Smoke Density

The Bosch Smoke Number was evaluated at six engine operation modes (described elsewhere) before and after each 200-hour test. The values of smoke number, indicating degree of blackness made on the paper filter when exhaust smoke was sucked through it, for the Lister and Deutz engine burning experimental fuels are arranged in Table XXVI.

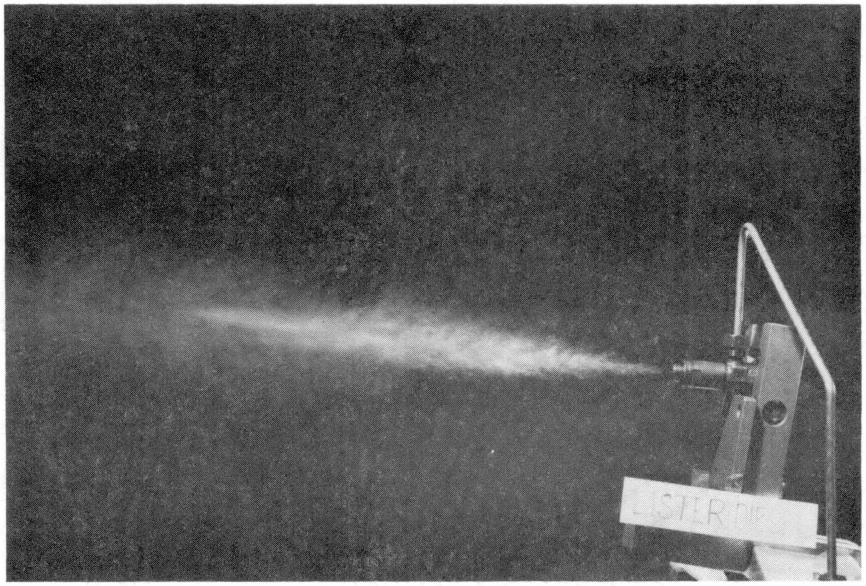


Figure 18. Spray Cone of the Injector Nozzle of the Lister Engine with Diesel Fuel

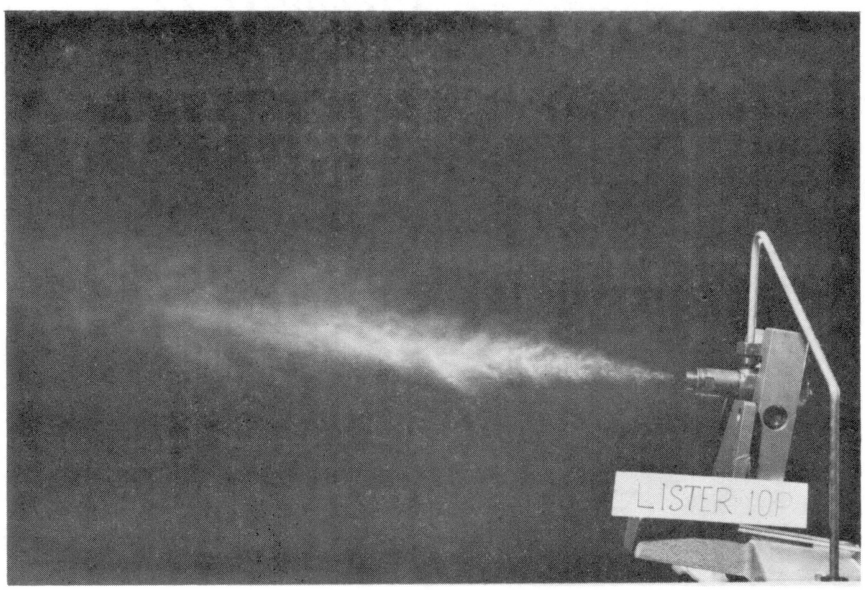


Figure 19. Spray Cone of the Injector Nozzle of the Lister Engine with 10% Peanut Oil and 90% Diesel Fuel

Figure 20. Spray Cone of the Injector Nozzle of the Lister Engine with 10% Cottonseed Oil and 90% Diesel Fuel

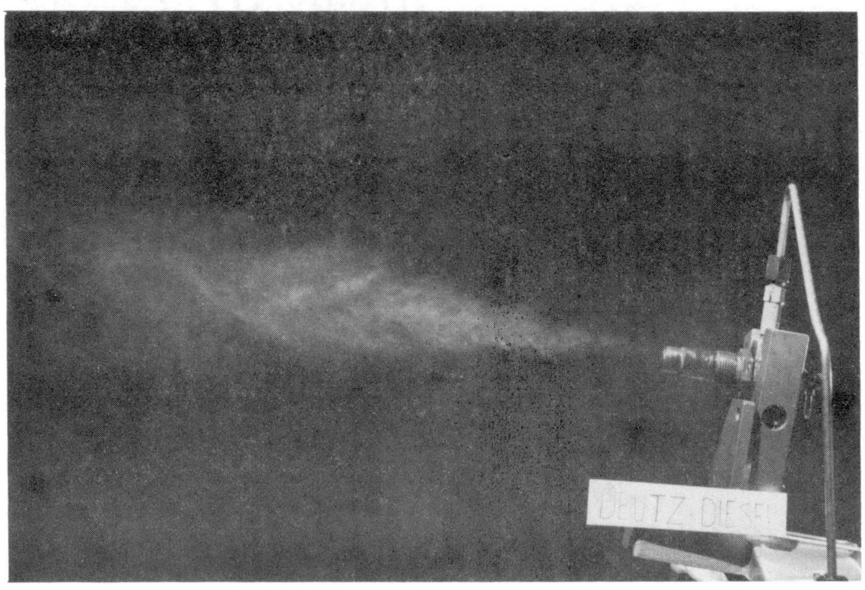


Figure 21. Spray Cone of the Injector Nozzle of the Deutz Engine with Diesel Fuel

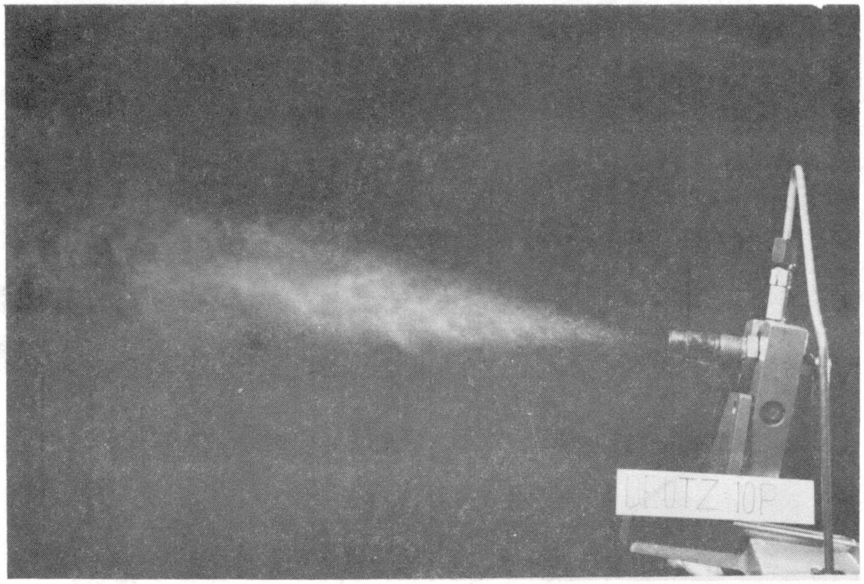


Figure 22. Spray Cone of the Injector Nozzle of the Deutz Engine with 10% Peanut Oil and 90% Diesel Fuel

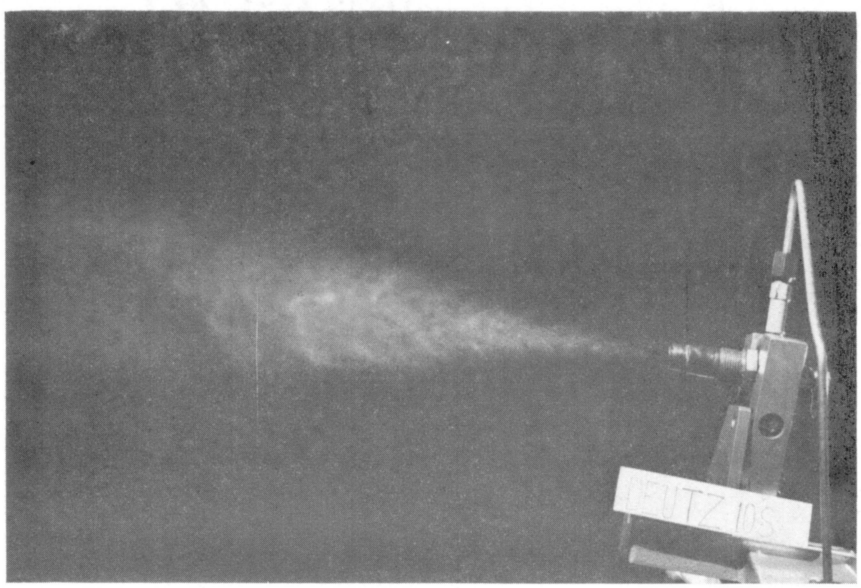


Figure 23. Spray Cone of the Injector Nozzle of the Deutz Engine with 10% Soybean Oil and 90% Diesel Fuel

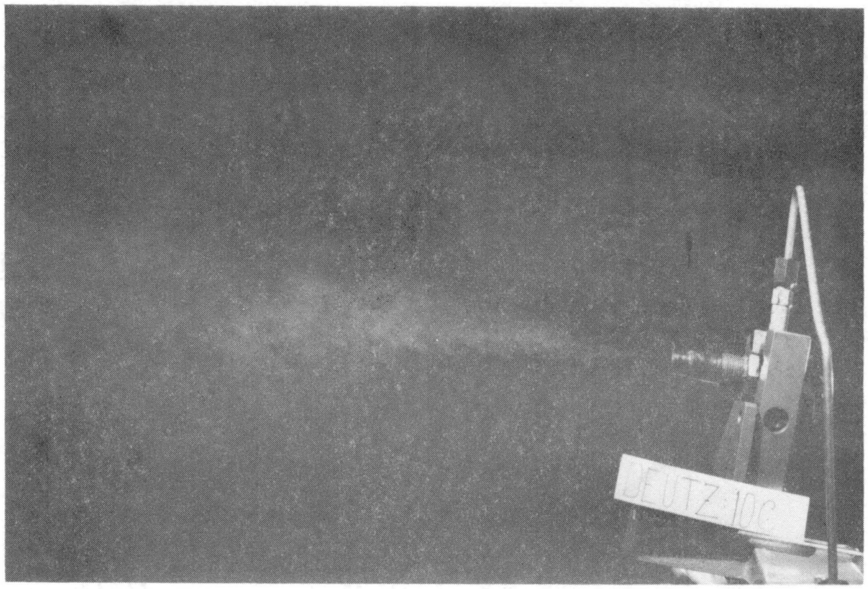


Figure 24. Spray Cone of the Injector Nozzle of the Deutz Engine with 10% Cottonseed Oil and 90% Diesel Fuel

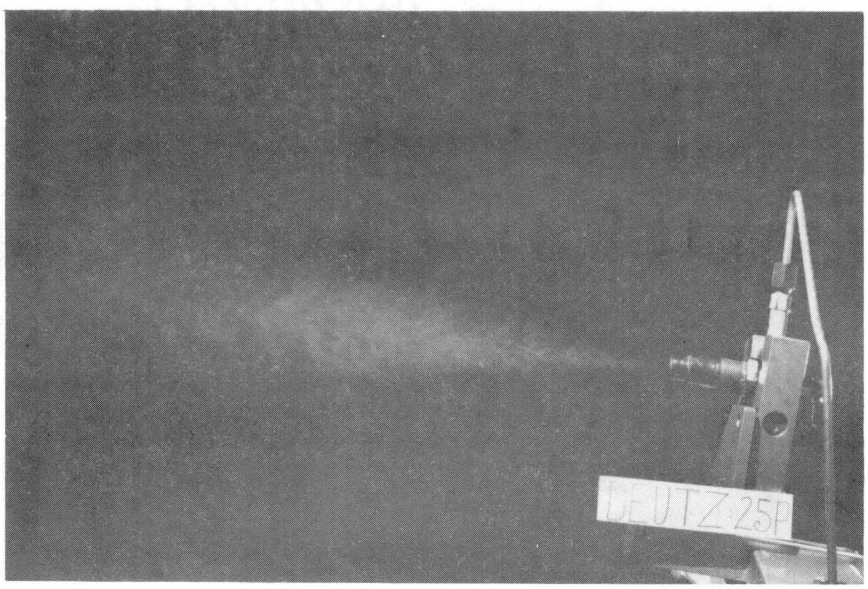


Figure 25. Spray Cone of the Injector Nozzle of the Deutz Engine with 25% Peanut Oil and 75% Diesel Fuel

TABLE XXVI

BOSCH SMOKE NUMBER OF TEST ENGINES WITH THE EXPERIMENTAL FUELS AT DIFFERENT POWER LEVELS BEFORE AND AFTER EACH 200-HOUR TEST

Engine Type	Fuel Type	Time of Test before/after 200-hr. test	Low Idle Speed Zero Load	Peak Torque Speed Zero Load	Peak Torque Speed 50% of Rated Load	Peak Torque Speed Full Load	Rated Speed Zero Load	Rated Speed 50% of Rated Load	Rated Speed Rated Load
Lister LT1	#2D	Before	1.1	1.8	1.8	0.8	0.5	1.4	2.2
		After	1.5	1.9	2.0	2.5	1.5	2.0	3.0
		Average (of before and after)	1.3	1.8	1.9	1.6	1.0	1.7	2.6
	10P90D	Before	1.0	1.5	1.0	3.5	1.8	1.0	4.3
		After	1.6	2.0	2.4	3.3	1.8	2.2	4.6
		Average	1.3	1.7	1.7	3.4	1.8	1.6	4.4
	10C90D	Before	1.4	1.4	2.0	3.4	2.1	2.8	4.6
		After	1.9	2.0	2.2	3.1	2.3	3.4	4.7
		Average	1.6	1.7	2.1	3.2	2.2	3.1	4.6
Deutz F1L511W	#2D	Before	0.2	0.65	0.9	1.15	0.7	0.9	0.8
		After	0.25	0.60	0.75	1.55	0.7	0.7	1.0
		Average	0.22	0.62	0.82	1.35	0.7	0.8	0.9
	10P90D	Before	0.2	0.3	1.0	1.3	0.8	1.3	3.0
		After	0.6	1.2	3.0	3.6	1.2	1.6	3.2
		Average	0.4	0.75	2.0	2.4	1.0	1.4	3.1
	10S90D	Before	0.5	0.9	1.4	2.1	0.9	1.0	1.4
		After	0.7	0.75	1.4	1.7	0.9	1.4	1.6
		Average	0.6	0.82	1.4	1.9	0.9	1.2	1.5
	10C90D	Before	0.5	0.6	1.8	3.0	0.7	1.4	2.5
		After	0.6	0.8	2.2	3.4	0.8	1.8	2.85
		Average	0.55	0.7	2.0	3.2	0.75	1.6	2.7
	25P75D	Before	0.6	0.7	1.2	1.3	0.75	1.10	1.1
		After	0.4	0.5	0.9	1.7	0.7	1.0	1.6
		Average	0.5	0.6	1.05	1.5	0.72	1.05	1.35

After each 200-hour test the smoke number increased from the pre-test values, in both engines. This happened possibly due to a decrease in efficiency of combustion caused by deposits of carbon around the combustion chamber components during the 200-hour test. Before starting another test, the engine was torn down, measurements made and reassembled after cleaning the valves, piston head, cylinder head, rings, manifolds. At rated speed and torque of the Lister engine, the average smoke number increased by 69% in using 10P90D and by 77% when using 10C90D as compared to the smoke level emitted while burning #2D. During the 200-hour test of the Deutz engine, the smoke levels were generally lower than that observed during the Lister engine test for all the experimental fuels. At rated speed and torque, the increase in average smoke number is shown in Table XXVII.

During the maximum power and fuel consumption test, the smoke number did not increase at all for the fuels having 10% vegetable oil and 90% diesel. A 10% increase in smoke number from that obtained using diesel fuel, was observed in burning the fuel 25P75D. The higher increase during the 200-hour endurance test was possiply due to long engine running period at various loads, developing carbon build-up around the combustion chamber components, and thereby hindering efficient and complete combustion.

Lubricating Oil Consumption and Quality

During each 200-hour test, the crankcase level was checked before each cold start. If the level was low, new oil was added. The average hourly consumption of lubricating oil during each of the tests for both engines are shown in Table XXVIII.

TABLE XXVII

INCREASE IN AVERAGE SMOKE NUMBER AT RATED POWER FOR ALTERNATE FUELS USED IN THE DEUTZ DIESEL ENGINE FROM THAT WITH DIESEL FUEL DURING 200-HOUR TEST

Fuel Type	Percent Increase in Smoke Number
10P90D	244
10S90D	67
10C90D	197
25P75D	50

TABLE XXVIII

AVERAGE HOURLY CONSUMPTION OF LUBRICATING OIL DURING 200-HOUR TEST

Engine Type	Fuel Type	Average Hourly Consumption ml/hr
Lister LT1	#2D	18.5
	10P90D	13.0
	10C90D	12.4
Deutz F1L511W	#2D	41.7
	10P90D	40.2
	10S90D	40.5
	10C90D	36.1
	25P75D	35.4

For the data when using the Lister engine burning #2D, the lubricating oil consumption was the highest and became less when the engine was running on alternate fuels. Goering and Fry (1983) also found that less lubricating oil was consumed by the engine burning hybrid fuels. The Deutz engine consumed more oil than the Lister engine during the test of all fuels. When the engine was burning alternate fuels, it consumed a lesser amount of lubricating oil. This reduction in oil consumption was possibly due to leakage of unburned fuel through the gaps between the piston rings and cylinder.

The Cleveland Technical Center, Inc., Ohio performed the physical and spectrochemical analysis of the lubricating oil samples taken during 200-hour tests. The results of the analysis are summarized in Table XXIX.

For the Lister engine burning diesel, the iron-content was the lowest whereas the iron content was much higher for the blends. The iron-content was the highest for the fuel 10P90D, indicating that more wear of rings, liners or crankshaft took place. The chromium content was almost double for the alternate fuels. Chromium in oil indicate the wear of rings. The higher copper content in case of diesel fuel indicate greater wear of bearings than that occurred in case of other fuels. The greater aluminum content means higher piston scuffing. The absence of nickel indicates there was no wear of valves and valve guides. The average viscosity of lubricating oil was lower for the blends, indicating leakage of unburned fuel around rings, necessiating less addition of lubricating oil. Average solid content (% insulubles) by volume is higher in case of blends implying that wear of engine internal parts was higher than that taken place when the engine was run on diesel.

In the case of the Deutz diesel engine, the metal content in the lubricating oil can be explained in a similar way. The iron-content for the alternate fuel (except 10P90D) is lower, indicating less wear of rings liners, and crankshaft. The chromium and copper content when using diesel were much higher than that which took place in using the diesel-vegetable oil blends and neat vegetable oils. The aluminum content

TABLE XXIX

WEAR METAL, INSOLUBLE AND VISCOSITY OF LUBRICATING OIL DURING 200-HOUR TEST*

Type of Engine	Type of Fuel Burned	Hours of Run	Amount of Metal, Ppm by weight						Viscosity at 37.8 C SUS	% Insolubles (by vol)	Remarks
			Iron	Chromium	Copper	Aluminum	Nickel	Manganese			
Lister LT1	#2D	60	72	4	47	7	0	2	656.3	0.2	1. No corrective action indicated by tests performed.
		105	56	4	36	5	0	2	667.4	0.2	2. Test results indicate wear metal levels are satisfactory.
		150	57	2	33	4	0	2	713.3	0.3	
		200	51	4	25	3	0	2	752.2	0.3	
Lister LT1	10P90D	60	84	8	19	13	0	2	704.9	0.2	1. "
		105	84	8	18	13	0	2	638.2	0.3	2. "
		150	83	6	16	12	0	2	668.8	0.3	
		200	114	7	16	16	0	2	668.8	0.4	
Lister LT1	10C90D	60	71	6	27	10	0	2	686.9	0.2	1. "
		105	80	6	25	10	0	2	664.6	0.2	2. "
		150	98	8	28	10	0	2	685.5	0.3	
		200	104	8	24	10	0	2	703.5	0.4	
Deutz F1L511W	#2D	60	25	3	20	4	0	1	735.5	0.2	1. "
		105	20	2	16	2	0	1	724.4	0.2	2. "
		150	20	4	29	2	0	1	768.9	0.3	
		200	32	1	35	2	0	1	781.4	0.3	
Deutz F1L11W	10P90D	60	27	2	9	2	0	1	728.6	0.2	1. "
		105	34	0	9	2	0	1	755.0	0.3	2. "
		150	35	1	12	1	0	1	814.8	0.3	
		200	33	2	22	1	0	1	659.0	0.3	

TABLE XXIX (Continued)

Deutz 10S90D F1L511W	60	15	2	11	6	0	1	663.2	0.2	1. "
	105	17	2	9	6	0	1	668.8	0.2	2. "
	150	16	0	7	6	0	1	673.0	0.2	
	200	11	2	7	5	0	1	652.1	0.2	
Deutz 10C90D F1L511W	60	20	3	7	5	0	1	621.5	0.2	1. "
	105	17	8	7	5	0	1	611.8	0.2	2. "
	150	15	2	6	5	0	1	650.7	0.2	
	200	11	1	5	5	0	1	615.9	0.2	
Deutz 25P75D F1L511W	60	24	3	13	6	0	1	609.0	0.1	1. "
	105	15	2	9	6	0	1	557.5	0.1	2. "
	150	12	2	7	6	0	1	590.0	0.1	
	200	11	2	5	6	0	1	578.4	0.1	
Reference Oil at 0 hours		3	1	0	0	0	1	554.8	0	

* The analysis was done by the Cleveland Technical Center, Inc. Ohio.

when using 10S90D, 10C90D and 25P75D is higher by several times. The average viscosity of the oil went down during use of hybrid fuels. Pischinger et al. (1983) and Strayer and Craig (1983) observed the reduction of oil viscosity in their respective test of engines with alternate fuels. The overall solid content in the lubricating oil in case of all experimental fuels did not change significantly. The solid content in the #2D test was a little higher partially due to initial wear of some parts such as the crank shaft, cam shaft, and cylinder liner which were not replaced during any of the 200-hour tests.

The Cleveland Technical Center, Inc., remarked after each analysis of oil that no corrective action (e.g. lubricating oil change, replacement of parts) was necessary for the engines during the tests. The results also indicated that wear metal level were satisfactory in all tests.

Wear of Engine Internal Parts

Following the guidelines recommended by the Engine Manufacturers' Association (Appendix A). The parts of engines which might undergo wear, were measured for dimension and mass before and after each 200-hour test. The results are shown in Table XXX. The change in dimension and mass was very small. While taking measurement, some change in mass was noticed in spite of no change in dimension. In writing the table, the parts which underwent wear for a particular fuel are mentioned in that particular row only. Data for the Lister engine indicate that mass of wear metal was greater when vegetable oils and blends were burned. This fact is also proved by the less accumulation of insoluble metals in the lubricating oil analysis of engines burning the same fuels. The

TABLE XXX

CHANGE IN DIMENSION AND WEIGHT OF SOME ENGINE PARTS DURING 200-HOUR TESTS

Type of Engine	Type of fuel	Designation of Parts	Change in Dimension, mm	Change in Weight, mg	Remarks
Lister LT1	#2D	Big end bearing inter. dia. (fitted)	0.004	40	No change was found in case of other measureable parts.
		Flywheel bearing inter dia.	0.051	130	
		Governor bearing inter. dia.	0.020	130	
		Cylinder bore (ave.)	0.051	---	
			TOTAL	300	
Lister LT1	10P90D	Big end bearing dia.	0.006	380	No change was found in case of other measureable parts.
		Flywheel bearing dia.	0.065	210	
		Governor bearing dia.	0.027	190	
		Intake valve stem dia.	0.025	70	
		Exhaust valve stem dia.	0.025	70	
		Cylinder bore (ave.)	0.025	90	
		Top ring width	0.025	350	
		2nd ring width	0.025	220	
		3rd ring width	0.025	560	
		4th ring width	0.050	1120	
			TOTAL	3190	

TABLE XXX (Continued)

Lister LT1	10C90D	Big end bearing dia.	0.004	0	No change was found in case of other measureable parts.
		Flywheel bearing dia.	0.025	365	
		Governor bearing	0.014	140	
		Exhaust valve stem dia.	0.025	10	
		Cylinder bore (ave.)	0.003	---	
			TOTAL	515	
Deutz F1L511W	#2D	Crank pin dia.	0.092	---	No change was found in case of other parts which might undergo wear
		Flywheel hub cia.	0.017	---	
		Governor hub dia.	0.017	---	
		Big end bearing dia.	0.945	920	
		Flywheel bearing dia.	0.936	840	
		Governor bearing dia.	0.936	810	
		Intake valve stem dia.	0.056	1060	
		Exhaust valve stem dia.	0.025	470	
		Piston skirt dia.	0.041	---	
		Wrist pin dia.	0.009	---	
		Bearing (small end)dia.	0.32	430	
		Top ring width	0.005	50	
		Mid ring width	0.011	30	
		Bottom ring width	0.022	10	
		Cylinder bore (ave.)	0.016	---	
			TOTAL	4620	
Deutz F1L511W	10P90D	Intake valve stem dia.	0.051	260	No change was found in case of other parts which might undergo wear
		Exhaust valve stem dia.	0.026	270	
		Piston bearing (small eng) dia.	0.009	100	
		Cylinder bore (ave.)	0.001	---	
			TOTAL	630	

TABLE XXX (Continued)

Deutz F1L511W	10S90D	Big eng bearing dia.	0.025		260	No change was found in case of other parts which might undergo wear
		Flywheel bearing dia.	0.026		220	
		Governor bearing dia.	0.026		110	
		Piston skirt dia.	0.016		---	
		Wrist Pin dia.	0.025		---	
		Bearing (small end) dia.	0.177		230	
		Cylinder bore (ave.)	0.076		---	
				TOTAL	820	
Deutz F1L511W	10C90D	Big end bearing dia.	0.051		520	No change was found in case of other parts which might undergo wear
		Flywheel bearing dia.	0.026		120	
		Governor bearing dia.	0.026		240	
		Intake valve stem dia.	0.051		50	
		Exhaust valve stem dia.	0.015		40	
		Piston skirt dia.	0.025		---	
				TOTAL	970	
Deutz F1L511W	25P75D	Big end bearing dia.	0.015		170	No change was found in case of other parts which might undergo wear
		Flywheel bearing dia.	0.0		0	
		Governor bearing dia.	0.016		310	
		Intake valve stem dia.	0.0		180	
		Exhaust valve stem dia.	0.0		260	
		Top ring width	0.0		70	
		Mid ring width	0.0		110	
		Bottom ring width	0.0		70	
				TOTAL	1160	

metal wear of the engine parts using the fuel, 10P90D was the highest in both Tables XXIX and XXX for the Lister engine.

From the results of the Deutz Engine Tests (Table XXX), it can be observed that wear of metals in #2D test was the highest in quantity followed by the wear in the tests with 25P75D, 10C90D, 10S90D and 10P90D. The initial wear of some parts such as the crank, cam, and cylinder liner, which were not replaced, might be responsible for greater amount of wear in the #2D test of the Deutz engine. Both engines completed all 200-hour tests without any deterioration in performance indicating no fault of the engines due to wear of parts.

Carbon Deposit on Engine Internal Parts

After completion of each 200-hour test with an experimental fuel, the engine was torn down and carbon deposit from cylinder head, piston head, rings, valves, valve guides, and injector nozzle tip was collected. The total amount of carbon deposit was measured as described earlier. The results for both engines are shown in Table XXXI. Figure 26 shows also the graphical representation. The Lister engine (direct injection) burning diesel-vegetable oil blends deposited the highest quantities of carbon. In the Deutz engine (indirect injection), the carbon deposits for the alternative fuels were greater than that collected after the diesel fuel test.

As found by Bruwer et al. (1980) and Quick et al. (1982), the carbon build-up in a single stage combustion engine (Lister LT1) was much higher than that in a double-stage combustion engine (Deutz F1L511W). A photographic display of carbon deposit on some parts before and after

200-hour test is made in Figures 27 to 33, from which a visual comparison can be made.

TABLE XXXI

MASS OF CARBON DEPOSIT ON ENGINE INTERNAL PARTS DURING 200-HOUR ENDURANCE TEST

Engine Type	Fuel Type	Amount of Carbon Deposit in mg.	% increase from #2D
Lister LT1	#2D	521	---
	10P90D	1438	176
	10C90D	1424	173
Deutz F1L511W	#2D	172	---
	10P90D	253	47
	10S90D	481	180
	10C90D	205	19
	25P75D	1015	490

Figure 34 shows the amount of carbon deposit collected on a piece of paper from the cylinder head, piston head, and valves of the Lister engine after 200-hour test with the fuel blend of 10% cottonseed oil and 90% #2D. During the experiment, no test run was stopped for engine failure due to carbon deposit.

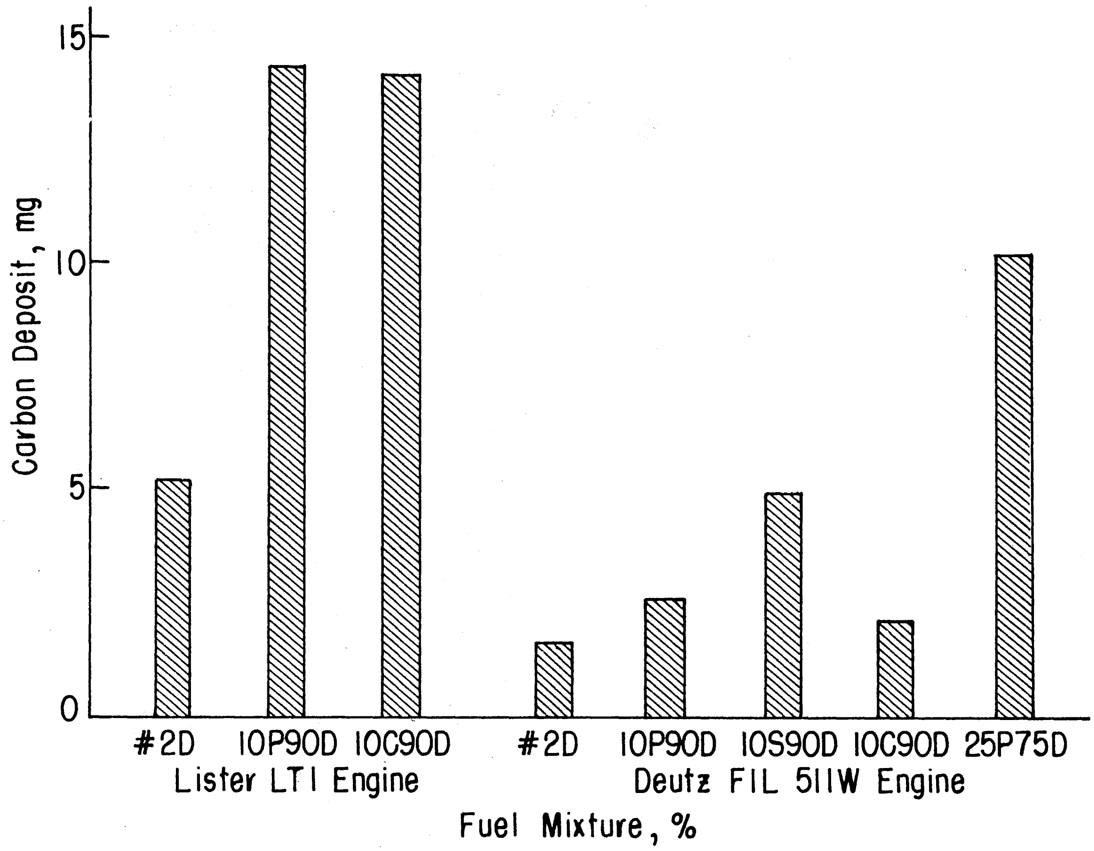
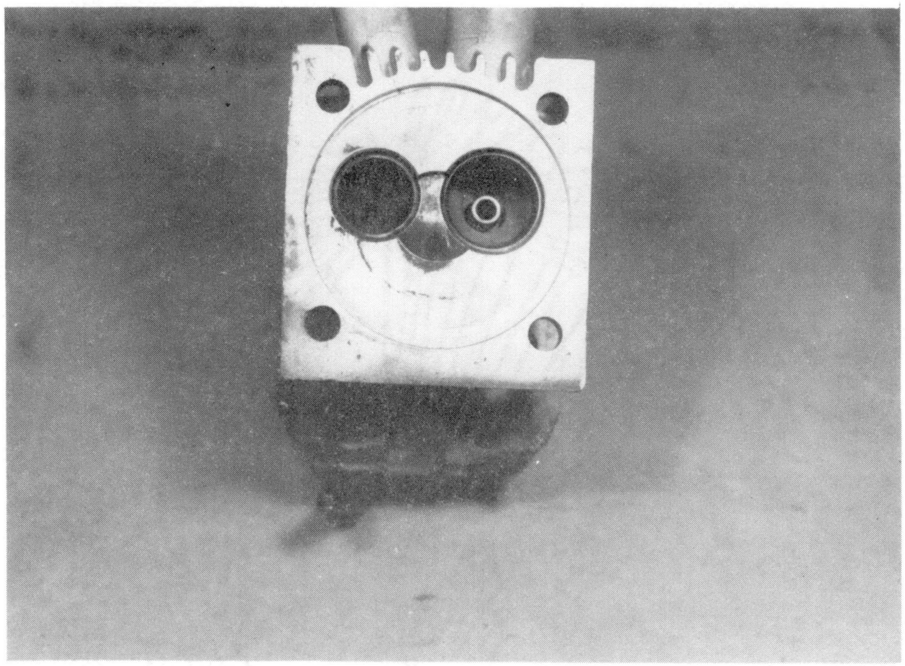


Figure 26. Carbon Deposit on the Internal Parts of the Lister and Deutz Diesel Engine Burning #2 Diesel and the Alternative Fuels



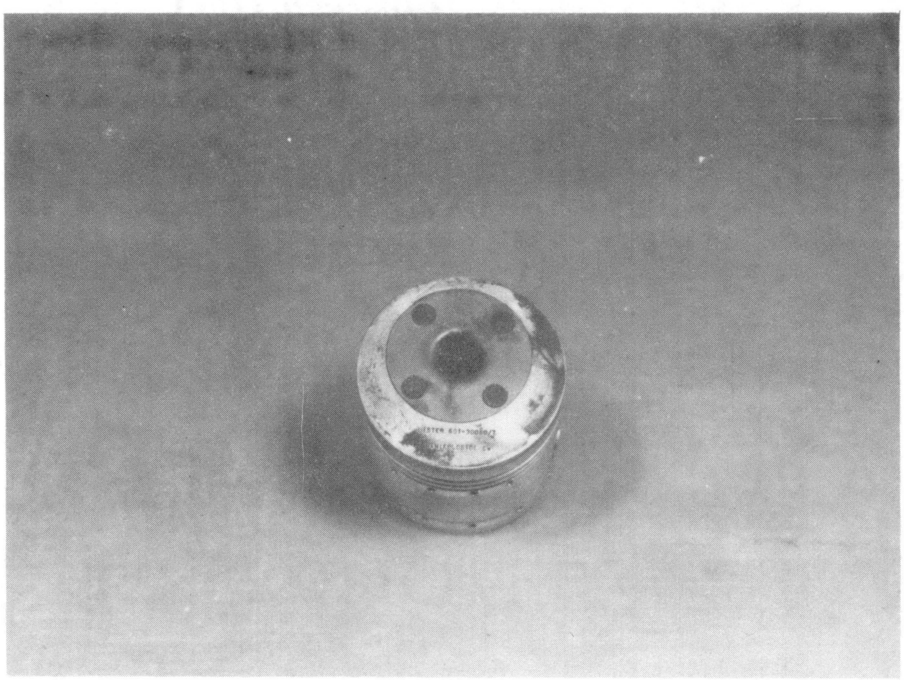


Figure 27. Cylinder Head (Top) and Piston Head (Bottom) of the Lister Engine before starting 200-hour Test

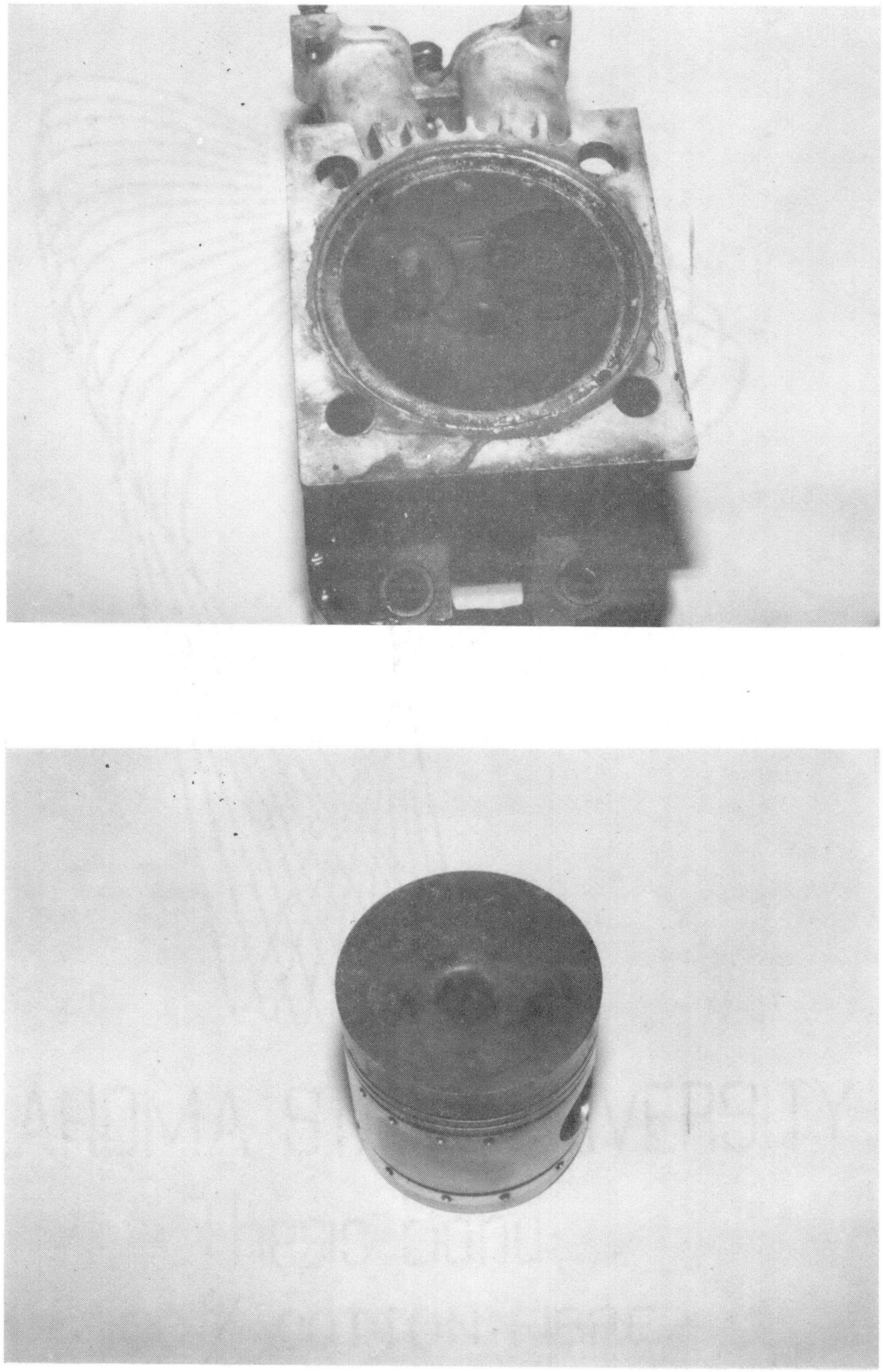


Figure 28. Carbon Deposit on Cylinder Head (Top) and Piston Head (Bottom) of the Lister Engine after 200-hour Test with #2 Diesel Fuel

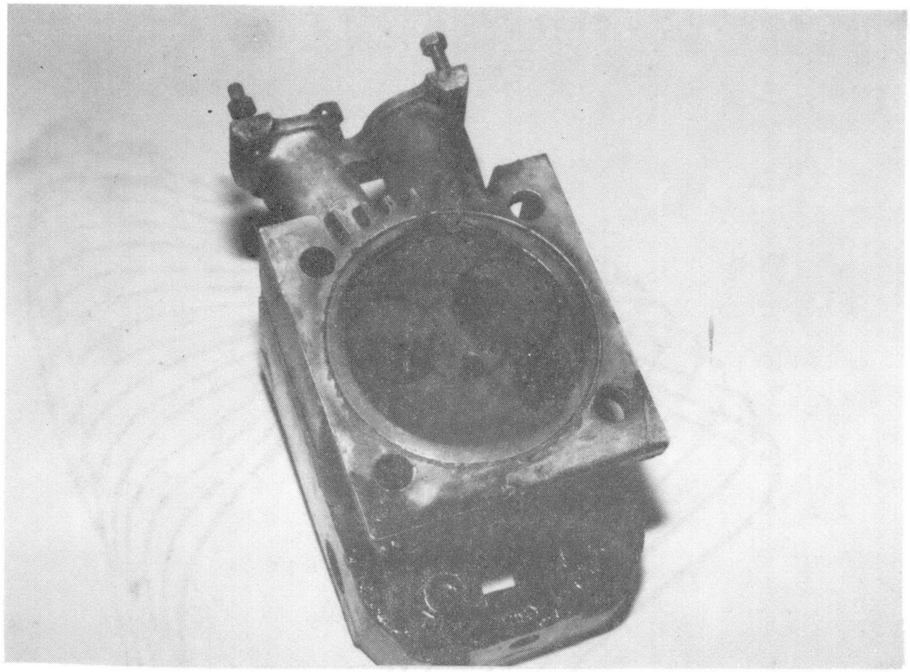


Figure 29. Carbon Deposit on Cylinder Head (Top) of Piston Head (Bottom) of the Lister Engine after 200-hour Test with 10% Peanut Oil and 90% Diesel Fuel Mixture

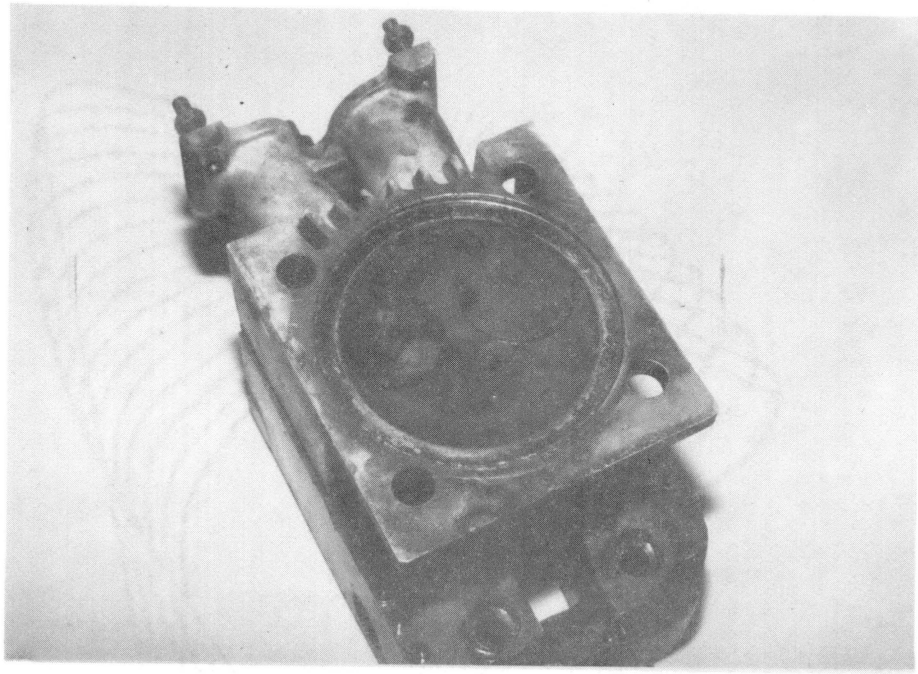


Figure 30. Carbon Deposti on Cylinder Head (Top and Piston Head (Bottom) of the Lister Engine after 200-hour Test with 10% Cottonseed Oil and 90% Diesel Fuel Mixture

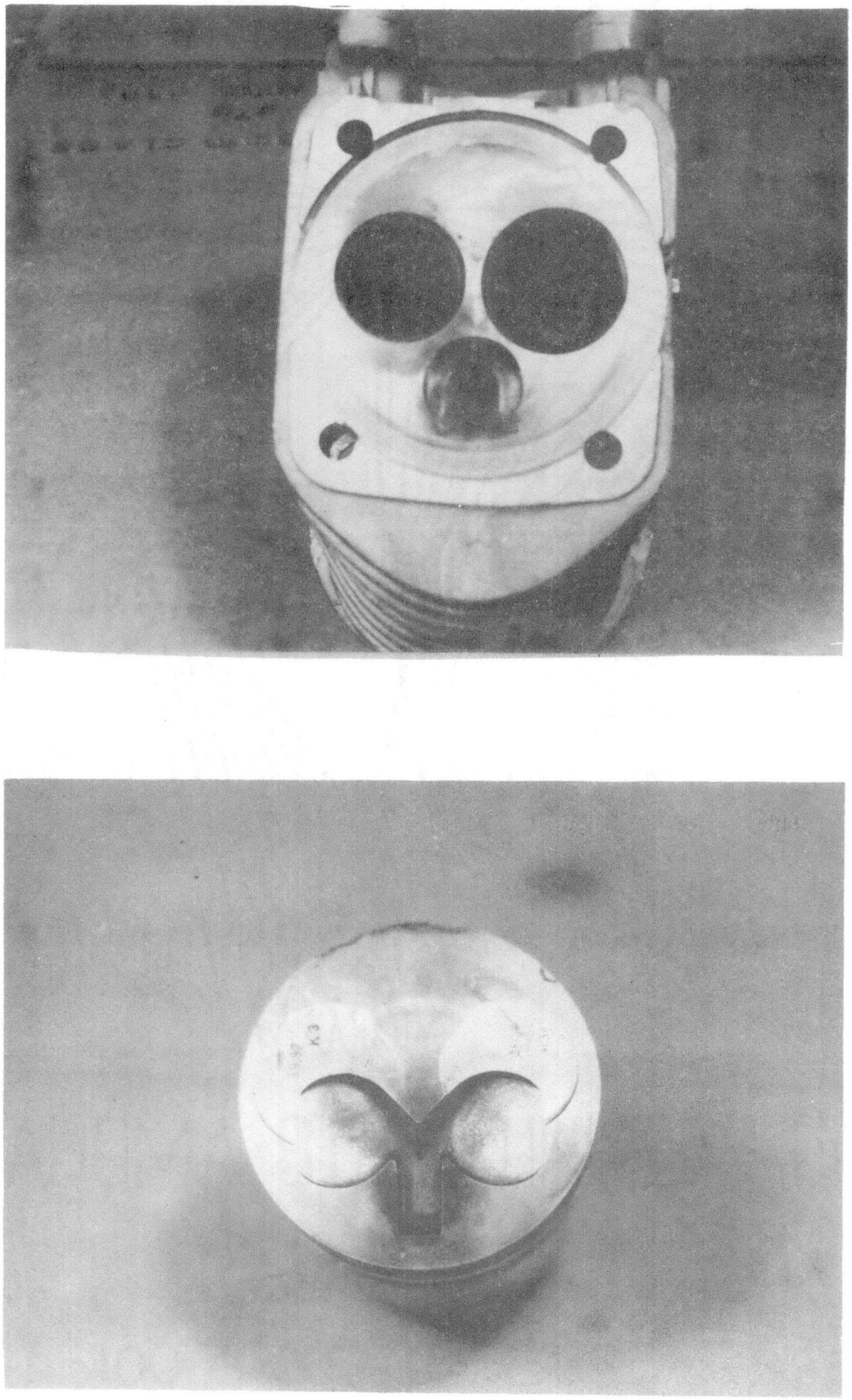


Figure 31. Cylinder Head (Top) and Piston Head (Bottom) of the Deutz Engine before Starting 200-hour Test

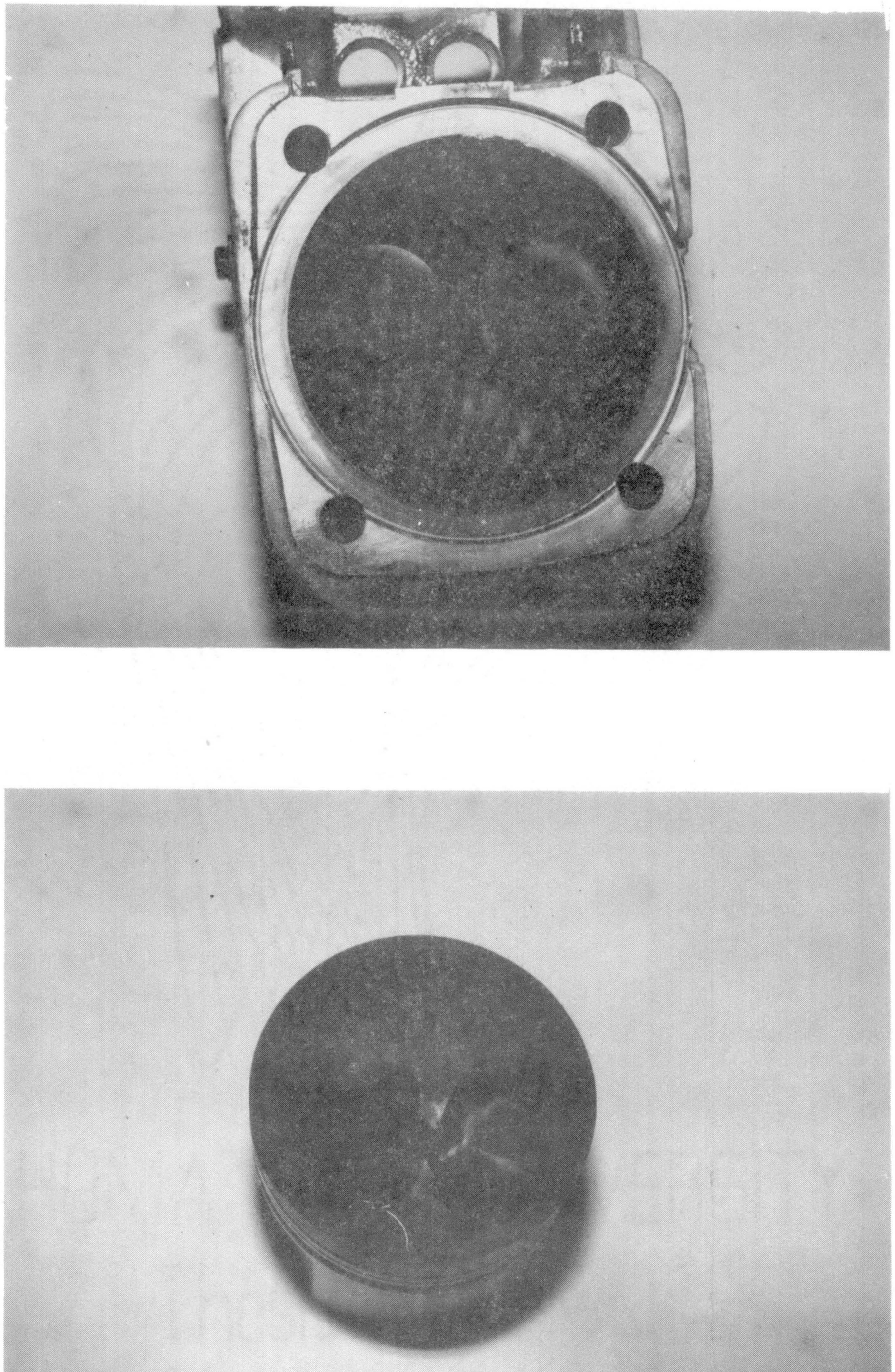


Figure 32. Carbon Deposit on Cylinder Head (Top) and Piston Head (Bottom) of the Deutz Engine after 200-hour Test with 10% Peanut Oil and 90% Diesel Fuel Mixture

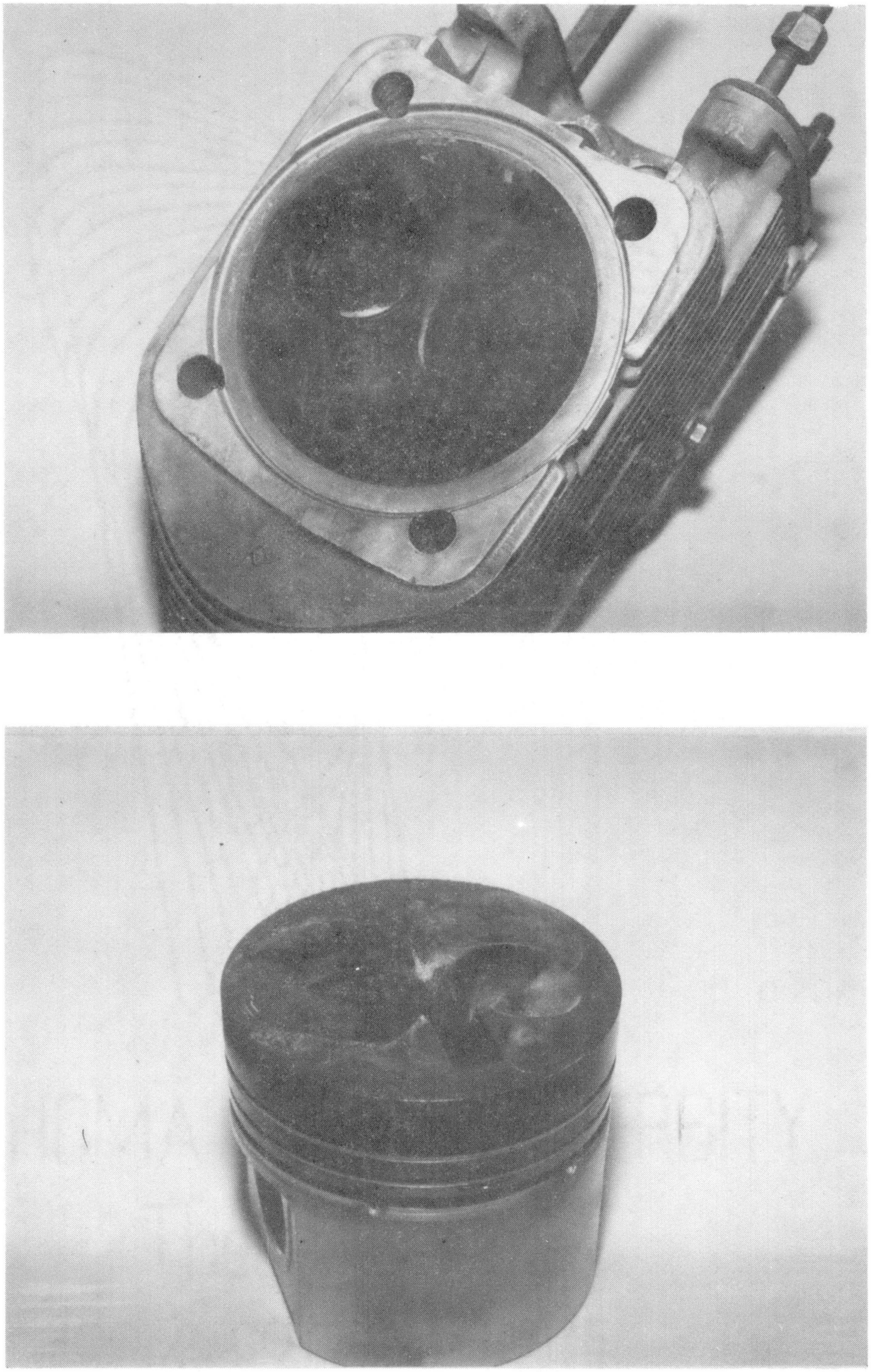


Figure 33. Carbon Deposit on Cylinder Head (Top) and Piston Head (Bottom) of the Deutz Engine after 200-hour Test with 10% Soybean Oil and 90% Diesel Fuel Mixture

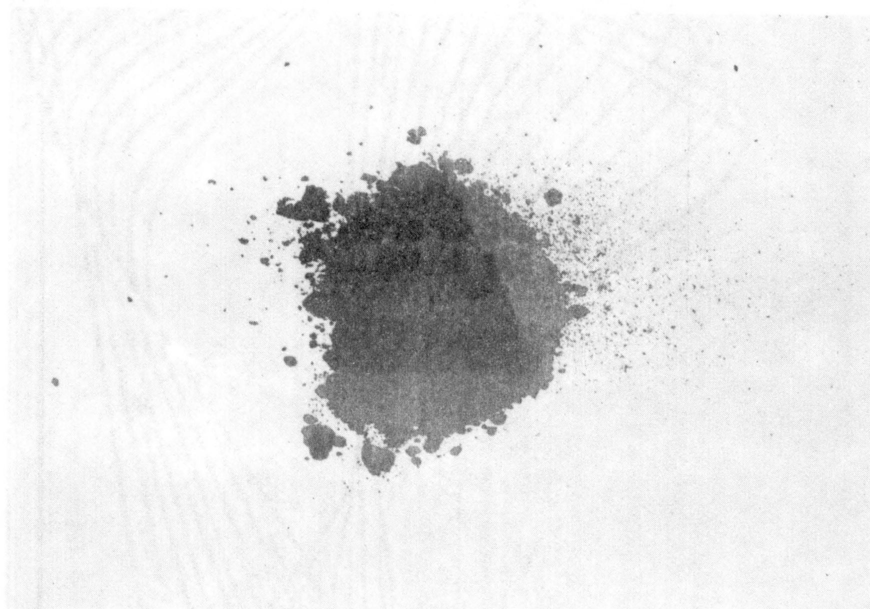


Figure 34. 1424 mg of Carbon Deposit Collected from All Parts of the Lister Engine after 200-hour Test with the Fuel Mixture of 10% Cottonseed Oil and 90% #2 Diesel

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

The performance, reliability, and durability of small diesel engines burning vegetable oil and its blends in different proportion with diesel fuel, were evaluated and compared to those of the engines burning neat diesel fuel. Degummed (primarily refined) peanut oil, soybean oil and cottonseed oil and the mixtures (by volume) of 10, 25% of them with 90, 75% of #2 diesel fuel, were tested as alternative fuel, with reference to #2 diesel as baseline. One single cylinder, naturally aspirated, air cooled direct injection diesel engine (Lister LT1) and one single cylinder, naturally aspirated, air cooled indirect injection diesel engine (Deutz F1L511W) were run for the experimental investigation. The engines were started on diesel fuel and switched to an alternate fuel (dual-fuel system) after warm-up and were then purged down to diesel fuel before shut-down. The power output, fuel consumption, thermal efficiency and exhaust smoke density of the engines run on test-fuels were determined with the help of an electric generator type dynamometer (Megatech, DG-100). The results of the tests were graphically represented for comparison of the performance of the engines burning alternative fuels to that burning reference diesel fuel. On the basis of the short term performance, two types of alternate fuels were selected for the

Lister engine and four types for the Deutz diesel (in addition to #2 diesel) for 200-hour durability screening test. The injector nozzle performance, exhaust smoke density, lubricating oil deterioration, wear of engine internal parts, and carbon deposit around the combustion chamber components of the engines burning baseline and alternate fuels were evaluated and compared.

Conclusions

For small, single cylinder, naturally aspirated, direct and indirect injection diesel engines, set to run on #2 diesel fuel, and are equipped with a dual-fuel provision to start on #2 diesel fuel, run on neat vegetable oils or vegetable oil/diesel blends, and then purge and shut down with #2 diesel fuel, the following conclusions are applicable:

1. Maximum power output would fall by 1-5%.
2. Fuel consumption would increase by 1-14% by mass.
3. Brake thermal efficiency would decrease by 1-10%.

   Initial tests of the small diesel engines with dual-fuel system suggest:

4. Injector performance, oil consumption, oil dilution, engine wear, carbon deposit, exhaust smoke density, would all remain within acceptable limits.
5. An indirect injection engine would show better performance in respect of power output, fuel consumption, thermal efficiency, reliability and durability than would the direct injection engine. As a result of the tests conducted in the laboratory, it appears that 10-25% (by volume) of vegetable oils, specifically peanut oil, soybean oil and cottonseed oil, with the rest of fuel blend being #2 diesel, would perform satisfactorily as an emergency diesel engine fuel.

Suggestions for Future Work

Short term performance and long term durability in the field conditions should be investigated fore more hours, and for more engines having additional accessories like turbo charger and turbo charge with inter cooler, in order to recommend vegetable oil and its blend as commericial fuels. To avoid densification of neat vegetable oil in a very cold environment, heating of fuel tank and fuel line should be evaluated. The diesel blends having a greater variety of vegetable oils should be tested and evaluated for performance to find an optimum mixture which should flow freely through filters within the normal working range of temperatures. An investigation into the modification of injector nozzle design is recommended for reduction of carbon deposit inside the combustion chamber while burning vegetable oil in the engines.

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APPENDIXES

APPENDIX A

AGRICULTURAL TRACTOR TEST CODE AND 200-HOUR SCREENING TEST FOR ALTERNATE FUELS

AGRICULTURAL TRACTOR TEST CODE
(ASAE Standard: ASAE S209.5 (SAE J708 JUN 80)

Section 2 - Detailed Description of Test Procedure

2.2 Mechanical power outlet performance

2.2.1 Maximum power-fuel consumption

2.2.1.1 The purpose of this run is to determine the maximum power as delivered through a mechanical power outlet to a dynamometer at the manufacturer's specified engine or mechanical power outlet speed; and to record the corresponding fuel consumption.

NOTE: This power can be measured through a belt pulley, power take-off shaft, or any other mechanical power outlet depending upon limitations of test equipment.

2.2.1.2 During the preparation for this run, the manufacturer shall establish fuel settings and ignition or injection timing, which shall remain unchanged throughout the test. The governor and the position of the manually operated governor control shall be adjusted to provide the high idle engine or power outlet speed specified by the manufacturer for maximum power operation.

2.2.1.3 Data recorded at intervals of no more than 10 min shall include engine crankshaft revolutions per minute, dynamometer revolutions per minute, mechanical power outlet shaft revolutions per minute, coolant temperature, wet- and dry-bulb air temperatures, fuel consumed, and dynamometer torque.

Speeds of engine, mechanical power outlet, and dynamometer shall be taken simultaneously. The coolant temperature shall be taken in the radiator top tank. The barometric pressure shall be recorded at the beginning of the run and at 1 h intervals thereafter. The duration of the run shall be a minimum of 2 h continuous operation.

NOTE: In order to determine belt slippage, simultaneous determinations of the revolutions of both drive and driven pulleys shall be taken at no-load for a minimum of 1000 revolutions of the drive pulley with the belt tension used for this run. Belt slippage shall be calculated as shown under Section 4. Belt tension shall be adjusted for optimum power and remain unchanged throughout run. Usually optimum power is obtained with approximately 1 percent slippage.

2.2.2 Varying power-fuel consumption

2.2.2.1 The purpose of this run is to determine fuel consumption and speed when power is varied.

2.2.2.2 All adjustments shall be the same as in paragraph 2.2.1.2.

2.2.2.3 Data recorded shall be the same as in paragraph 2.2.1.3. The duration of the run shall be for 2 h of continuous operation.

2.2.2.4 The run shall consist of six power settings, each to be run for a period of 20 min in the following order:

(a) 85 percent of dynamometer torque obtained at maximum power, run 2.2.1.

(b) Zero dynamometer torque.

(c) One-half of 85 percent of dynamometer torque obtained at maximum power, run 2.2.1.

(d) Dynamometer torque at maximum power.

(e) One-quarter of 85 percent of dynamometer torque obtained at maximum power, run 2.2.1

(f) Three-quarters of 85 percent of dynamometer torque obtained at maximum power, run 2.2.1.

NOTE: These percentages represent long and continuous past practice and are necessary to maintain continuity in procedure and meaning of the results.

200-HOUR SCREENING TEST FOR ALTERNATE FUELS

A Recommendation to the Northern Agricultural Energy Center, United States Department of Agriculture, Peoria, IL 61604, from the Engine Manufacturer's Association (EMA). September 1, 1982.

Research on/or testing of renewable fuels (i.e. vegetable oils--neat, blended or modified) for diesel engines is in progress or being planned at many locations. Previous studies have limited value because conditions and procedures were unique to each test.

An advisory committee with representation from USDA, agricultural experiment stations, engine (tractor) manufacturers and fuel additive suppliers to advise on procedures for engine tests of renewable fuels has been organized and is coordinated from NAEC, Peoria.

The Engine Manufacturer's Association (EMA), a trade association of 21 international engine manufacturers, has proposed at the request of the United States Department of Agriculture, a 200-hour preliminary durability screening test to access the potential impact of alternate fuels on diesel engine durability.

The test is intended for research and development purposes and is designed to try to initiate durability problems in a reasonable amount of test time. Successful completion of the test is no assurance that the fuel will be acceptable. However, the test will eliminate some candidate fuels, and patterns of performance and engine durability will be uniformely evaluated for all test fuels.

The advisory committee has adopted the EMA 200-hour screening test for farm tractor engine studies. Anyone contemplating engine testing of renewable fuels, or in an advisory or consultative role to such a project, is encouraged to follow this test procedure:

1. FUEL TEST SERIES:

   A fuel test series shall include a 200-hr. baseline test of the engine, followed by one or more 200-hr. tests of alternate fuels for comparison under similar conditions.

2. FUELS TO BE TESTED:

   a) Baseline test fuel: Phillips 2D Reference Fuel (P2D).

   b) Vegetable oil/P2D blends and modified or hybridized fuels should be specified and tested, starting with the experimental fuel least likely to cause engine damage followed by tests with fuels in order of increasing likelihood of engine damage. (NOTE: Commercial grade diesel fuels are not advised by the committee for the official 200-hr. screening test because of other variable properties. If commercial grade fuel must be used, its properties should be extensively tested and reported with the engine test results.)

c) Fuel additives: to be determined and specified.

3. FUEL CHARACTERIZATION AND DESCRIPTION TO INCLUDE:

a) Generic name, degree of refinement, source, percent of total mix for each energy component.

b) Gross caloric value; net caloric value. (may be specified as Btu/lb or Btu/gal.)

c) Viscosity at 100C and 40C.

d) Cetane number; Iodine Value; Wax Content; Phosphatide Content; Fatty acid profile by gas chromatography.

4. ENGINE WEAR OBSERVATIONS AND MEASUREMENTS:

a) Each 200-hr. fuel test to commence with new liners, rings, pistons, injector tips, valves, valve seat inserts and guides. (Other parts to be in good condition.)

b) Dimensions of liners and rings, and weight* of rings (and other parts as experience may indicate) to be measured before and after each 200-HOUR TEST.

*Weight to be determined after removal of any deposits.

c) All components of the engine that are likely to be affected by use of the fuel are to be observed, checked, and measured for proper function and for specification tolerances. Included are upper cylinder, cylinder head, induction and exhaust systems, turbo-charger, fuel injection system, and the entire lubrication system.

d) Components such as cylinder heads, injector bodies, valve lifters, cam shaft and bearings, and turbo charger can be cleaned and reused if within manufacturer's specifications.

e) Injectors (tips) will be inspected and performance checked after each test.

f) Parts that fail due to non-fuel related causes are to be replaced and the test continued.

g) There are to be no engine or parts modifications during a fuel test series.

5. CRITERIA FOR FUEL/ENGINE FAILURE:

a) Performance: A drop in power of 5% or more that cannot be corrected with minor adjustments (normal field adjustments) during the 200-hr. test. (Injector nozzles may be replaced to complete a test but this would constitute a failure.)

b) Durability:

1. Failure to complete 200 hours of EMA TEST CYCLE for any reason related to the test fuel.

*2. Measurement of blowby during testing is a convenient way of monitoring gross changes in engine performance which may be due to events such as ring sticking. Blowby measurement is optional and, if desired, need only be performed periodically (every 50 hours).

*c) Lubricating Oil (checked daily after warm-up):

1. Viscosity: A change of 50% from new oil value.

2. Dispersancy: Any indication of failure of dispersion. (Blotter spot test acceptable.)

**d) Engine Life (post inspection): Excessive wear that would extrapolate to a 50% or greater reduction in engine life based on the manufacturer's guidelines and experiences. Wear inspection should include, but is not limited to:

1. Piston, ring and liner wear or scuffing
2. Bearing wear
3. Cam and follower wear
4. Valve guttering

*Category (b) 2 and (c) will allow termination of the test just prior to a total engine disaster.

**Category (d) will require knowledge of normal engine wear in that area of the world where the alternate fuel is being considered, recognizing geographic variability of diesel fuel quality and the kinds and amounts of impurities.

6. LUBRICATING OIL:

a) High detergent type CD to be used.

b) One lot of lube oil sufficient for the test series should be procured.

c) Physical properties and engine wear contaminants (by chemical analysis) to be recorded at 0, 50, 100, 200 hours.

d) Crankcase level to be checked before each cold start. If oil is low oil should be added. Records of oil consumption should be kept.

e) Oil and oil filter change interval to be as recommended by the engine manufacturer, but not less than 100 hours.

7. EMA BREAK-IN SCHEDULE (90 minutes). A new or re-built engine is to be broken in with P2D fuel before each test as follows:

STEP	SPEED	POWER	MINUTES
1	Low Idle	Idle	10
2	1/2 Rated	Idle	10
3	3/4 Rated	1/2 Rated	15
4	Rated	Rated	55
			90

8. POWER AND FUEL CONSUMPTION TESTS:

To be in accord with SAE test procedures.

9. EXHAUST EMISSIONS:

a) Emission measurements for HC, CO, NO_x, and Smoke are optional. If undertaken, measurements should be made before and after each 200-hour test.

b) The following engine operation modes should be used.

(1) low idle speed, zero load

(2) peak torque speed (*) at zero load

(3) peak torque speed (*) at 50% load

(4) peak torque speed (*) at 100% load

(5) rated speed at zero load

(6) rated speed at 50% load

(7) rated speed at 100% load

10. FUEL PRESSURE:

To be monitored continuously and filters replaced as needed.

11. EMA TEST CYCLE (3-hours):

STEP	SPEED	TORQUE	POWER	DURATION-MIN
1	Rated	---	Rated*	60
2	85%	Max	95%	60
3	90%	28%	25%	30
4	Low Idle	0	0	30
				180

Weighted average power = 69%

*Turbo charged engines should be tested at their highest power rating (use of derated engines is not advised).

12. PRELIMINARY DURABILITY SCREENING TEST (200 hours):

Five consecutive test cycles are to be run without stopping the engine, followed by a nine hour (or longer) cold shut down (normal interior ambient temperature). Test duration is 200 hours of EMA cycle operation.

NOTE: Engine Manufacturers Association (EMA) and its members disclaim liability from any cause whatsoever related to the use of this test procedure.

(The EMA 200-hour fuel screening test would be only preliminary to many more specific tests were an engine manufacturer to consider commercial applications of its equipment on non-specifications fuels.)

Specific further information is available from Northern Agricultural Energy Center, 1815 N. University Street, Peoria, IL 61604.

APPENDIX B

VARYING POWER AND FUEL CONSUMPTION DATA

VARYING POWER AND FUEL CONSUMPTION DATA

Lister LT1 Engine

Fuel: #2D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
2.89	3400	1.000	0.348	2.87	17.2	23.3	74.00
0.00	3600	0.595	---	---	17.2	23.3	74.00
1.49	3500	0.833	0.559	1.79	17.2	23.3	74.00
2.98	3000	0.895	0.300	3.33	17.2	23.3	74.00
0.767	3600	0.641	0.835	1.20	17.2	23.3	74.00
2.24	3500	0.923	0.412	2.43	17.2	23.3	74.00
1.74	3433	0.814	0.468	2.14	17.2	23.3	74.00

Fuel: 10P90D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
2.64	3100	0.811	0.334	3.00	16.0	18.30	74.10
0.00	3500	0.583	---	---	16.0	18.30	74.10
1.45	3400	0.793	0.547	1.83	16.0	18.30	74.10
2.98	3000	0.899	0.301	3.32	16.0	18.30	74.10
0.746	3500	0.709	0.951	1.05	16.0	18.30	74.10
2.11	3300	0.886	0.420	2.38	16.0	18.30	74.10
1.65	3300	0.780	0.473	2.11	16.0	18.30	74.10

Fuel: 10S90D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
2.64	3100	0.909	0.344	2.91	18.9	21.10	74.00
0.00	3200	0.540	---	---	18.9	21.10	74.00
1.32	3100	0.752	0.570	1.75	18.9	21.10	74.00
2.98	3000	1.03	0.347	2.88	18.9	21.10	74.00
0.681	3200	0.540	0.793	1.26	18.9	21.10	74.10
1.98	3100	0.799	0.403	2.48	18.9	21.10	74.10
1.60	3117	0.762	0.476	2.10	18.9	21.10	74.10

Fuel: 10C90D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
2.64	3100	0.860	0.326	3.07	20.3	23.3	74.0
0.00	3600	0.592	---	---	20.3	23.6	74.0
1.32	3100	0.873	0.661	1.51	20.3	23.6	74.0
2.98	3000	1.910	0.305	3.27	20.3	24.1	74.0
0.770	3600	0.637	0.827	1.21	20.3	24.1	74.0
2.21	3100	0.945	0.428	2.34	20.3	24.1	74.0
1.65	3250	0.802	0.486	2.06	20.3	23.8	74.0

Fuel: 25P75D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
2.66	3400	1.020	0.383	2.61	21.7	23.9	73.75
0.00	3500	0.587	---	---	21.7	23.9	73.75
1.33	3400	0.910	0.684	1.46	21.7	23.9	73.75
2.88	3000	0.898	0.312	3.20	21.7	23.9	73.75
0.69	3500	0.608	0.882	1.13	21.7	23.9	73.75
2.00	3400	0.956	0.478	2.10	21.9	24.4	73.75
1.59	3367	0.830	0.522	1.92	21.7	23.9	73.75

Fuel: 25S75D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
2.64	3300	1.037	0.393	2.55	23.0	26.7	73.75
0.00	3600	0.619	---	---	23.0	26.7	73.75
1.24	3500	0.703	0.567	1.76	22.7	26.7	73.75
2.85	3000	0.954	0.335	2.99	22.7	26.7	73.75
0.64	3600	0.664	1.04	0.964	22.7	26.7	73.75
1.86	3500	0.899	0.483	2.07	22.7	26.7	73.75
1.54	3417	0.812	0.564	1.77	22.8	26.7	73.75

Fuel: 25C75D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
2.64	3300	1.050	0.397	2.51	18.9	20.8	73.80
0.00	3600	0.629	---	---	18.9	20.8	73.80
1.19	3350	0.859	0.722	1.38	18.9	21.9	73.80
2.85	2950	0.944	0.331	3.02	18.9	21.9	73.80
0.62	3500	0.680	1.099	0.917	18.9	21.9	73.80
1.76	3300	0.917	0.521	1.92	18.9	21.9	73.80
1.51	3334	0.846	0.560	1.78	18.9	21.5	73.80

Fuel: 100P

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
2.64	3300	1.051	0.398	2.51	20.0	23.9	73.83
0.00	3500	0.676	---	---	20.0	23.9	73.83
1.21	3400	1.058	0.875	1.14	20.3	23.9	73.83
2.86	3000	0.975	0.341	2.93	20.3	23.9	73.83
0.62	3500	0.691	1.115	0.897	20.3	23.9	78.83
1.78	3350	1.081	0.607	1.65	20.8	24.4	73.83
1.52	3342	0.922	0.607	1.65	20.3	24.0	73.83

Fuel: 100S

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
2.90	3400	1.245	0.429	2.33	14.2	18.3	74.40
0.00	3500	0.621	---	---	14.2	18.3	74.40
1.47	3450	0.715	0.486	2.06	14.4	18.9	74.40
2.98	3000	1.090	0.366	2.73	14.4	18.9	74.40
0.746	3500	0.781	1.046	0.956	14.4	18.9	74.40
2.17	3400	1.038	0.478	2.09	16.1	20.5	74.40
1.71	3375	0.915	0.535	1.87	14.6	19.0	74.40

Fuel: 100C

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
2.86	3350	1.20	0.419	2.38	14.4	20.0	74.30
0.00	3500	0.646	---	---	14.4	20.0	74.30
1.45	3400	0.881	0.607	1.62	16.7	21.4	74.30
2.98	3000	1.166	0.391	2.56	16.7	21.4	74.30
0.746	3500	0.728	0.976	1.02	16.7	21.4	74.30
2.17	3400	1.014	0.467	2.14	15.5	20.5	74.30
1.70	3358	0.939	0.552	1.81	15.7	20.8	74.30

DEUTZ F1L511W

Fuel: #2D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
7.94	2800	2.436	0.307	3.26	12.5	15.0	74.10
0.00	3000	0.928	---	---	12.5	15.0	74.10
4.25	3000	1.636	0.385	2.60	12.7	15.5	74.10
8.35	2500	2.339	0.280	3.57	12.7	15.5	74.10
2.13	3000	1.218	0.572	1.75	12.7	16.1	74.10
6.06	2850	2.032	0.335	2.98	12.7	16.1	74.10
4.79	2859	1.765	0.368	2.71	12.6	15.5	74.10

Fuel: 10P90D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
8.09	2850	2.451	0.303	3.30	9.4	12.9	74.00
0.00	2950	0.965	---	---	9.4	12.9	74.00
4.11	2900	1.678	0.408	2.45	9.5	12.9	74.00
8.35	2500	2.447	0.293	3.41	9.5	12.9	74.00
2.09	2950	1.236	0.591	1.69	9.6	13.1	74.00
6.04	2850	1.989	0.329	3.04	9.6	13.1	74.00
4.78	2833	1.794	0.375	2.66	9.5	12.9	74.00

Fuel: 10S90D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
8.40	2900	2.567	0.306	3.27	11.7	17.8	74.40
0.00	3000	0.982	---	---	11.7	17.8	74.40
4.27	2950	1.691	0.396	2.52	12.2	18.0	74.40
8.52	2500	2.510	0.295	3.39	12.2	18.0	74.40
2.17	3000	1.299	0.598	1.67	12.2	18.5	74.40
6.39	2900	2.000	0.314	3.18	12.2	18.5	74.40
4.96	2875	1.843	0.372	2.69	12.0	18.1	74.40

Fuel: 10C90D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
8.69	3000	2.548	0.293	3.41	14.2	21.39	73.60
0.00	3050	0.972	---	---	14.2	21.39	73.60
4.35	3000	1.651	0.379	2.63	14.4	21.9	73.60
9.21	2700	2.56	0.278	3.59	14.4	21.9	73.60
2.21	3050	1.28	0.581	1.72	15.0	22.2	73.60
6.52	3000	2.00	0.307	3.26	15.0	22.2	73.60
5.16	2967	1.84	0.356	2.81	14.5	21.8	73.60

Fuel: 25P75D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
8.31	2900	2.597	0.312	3.20	17.5	25.5	73.45
0.00	3000	0.974	---	---	18.0	25.6	73.45
4.30	3000	1.672	0.389	2.57	18.0	25.6	73.45
8.94	2650	2.482	0.277	3.60	18.5	26.0	73.45
2.15	3000	1.220	0.568	1.76	18.5	26.0	73.45
6.33	2950	2.084	0.329	3.04	18.5	26.0	73.45
5.00	2917	1.838	0.367	2.72	18.2	25.8	73.45

Fuel: 25S75D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
8.24	2900	2.533	0.307	3.25	16.8	20.8	72.95
0.00	3000	0.986	---	---	16.8	20.8	72.95
4.19	2950	1.653	0.395	2.53	16.5	20.0	72.95
9.01	2700	2.572	0.285	3.50	16.5	20.0	72.95
2.13	3000	1.291	0.606	1.65	16.5	20.0	72.95
6.29	2950	2.025	0.322	3.11	16.8	20.2	72.95
4.98	2917	1.843	0.370	2.70	16.6	20.3	72.95

Fuel: 25C75D

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
8.24	2900	2.500	0.303	3.30	17.5	20.0	72.00
0.00	3000	0.974	---	---	17.5	20.0	72.00
4.19	2950	1.644	0.392	2.55	17.1	19.61	72.00
9.01	2700	2.598	0.288	3.47	17.1	19.61	72.00
2.13	3000	1.239	0.582	1.72	17.1	19.61	72.00
6.29	2950	1.967	0.313	3.20	17.2	20.17	72.00
4.98	2917	1.820	0.365	2.74	17.2	19.8	72.00

Fuel: 100P

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
7.21	2900	2.534	0.351	2.85	13.9	16.2	72.30
0.00	3000	1.102	---	---	13.9	16.2	72.30
3.67	2950	1.791	0.488	2.05	13.6	16.1	72.30
8.00	2500	2.375	0.297	3.37	13.6	16.1	72.30
1.86	3000	1.390	0.747	1.34	13.6	16.1	72.30
5.49	2950	2.119	0.386	2.59	12.8	15.5	72.30
4.37	2883	1.896	0.434	2.30	13.6	16.0	72.30

Fuel: 100S

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
7.96	2950	2.764	0.347	2.88	11.38	15.5	73.95
0.00	3000	1.128	---	---	11.38	15.5	74.00
4.01	2975	1.871	0.466	2.14	10.83	15.0	74.00
8.20	2500	2.400	0.293	3.42	10.83	15.0	74.00
2.02	3000	1.467	0.726	1.37	10.83	15.0	74.00
5.97	2950	2.276	0.381	2.62	10.5	15.0	74.00
4.69	2896	1.984	0.423	2.36	10.9	15.1	74.00

Fuel: 100C

Brake Power kW	Crank Shaft Speed Rpm	Fuel kg per hour	Consumption kg per kW.hr	Power Output kW.hr per kg	Temperature Air Wet Bulb	Degrees C Air Dry Bulb	Barometer cm of Mercury
7.52	2900	2.597	0.345	2.89	7.2	11.7	74.50
0.00	3000	1.109	---	---	7.2	11.7	74.50
3.82	2950	1.804	0.472	2.12	7.5	12.2	74.50
8.15	2500	2.380	0.292	3.42	7.5	12.2	74.50
1.92	3000	1.366	0.711	1.41	8.3	13.3	74.50
5.66	2950	2.129	0.376	2.66	8.3	13.3	74.50
4.52	2883	1.897	0.420	2.37	7.7	12.4	74.50

2

VITA

Mohammed Abdul Mazed

Candidate for the Degree of

Doctor of Philosophy

Thesis: TEST OF VEGETABLE OIL AS FUEL IN DIRECT AND INDIRECT INJECTION DIESEL ENGINE

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Faridpur, Bangladesh, February 17, 1947, the son of Mr. and Mrs. Saberuddin Ahmed; married to Halima Khatun in 1974; daughter, Maliha, born on September 3, 1981.

Education: Received Secondary School Certificate from Habashpur K. Raj High School, Faridpur, Bangladesh, and completed higher secondary education from the Rajendra College, Faridpur, Bangladesh, in 1965; received the degree of Bachelor of Science in Mechanical Engineering from the Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, in 1969; received Master of Agricultural Engineering from the National College of Agricultural Engineering, Silsoe, Bedford, England in September, 1976; completed the requirements for the Doctor of Philosophy degree at Oklahoma State University in May, 1984.

Professional Experience: Assistant Engineer with the Bangladesh Machine Tools Factory, Joydebpur, Dhaka, 1970-1972; Member of the Faculty of Agricultural Engineering, Bangladesh Agricultural University, Mymensingh, Bangladesh, 1972-1978; Head of Agricultural Engineering Division, Bangladesh Agricultural Research Institute, Joydebpur, Dhaka, 1978-1980; Graduate Research Assistant in the Agricultural Engineering Department, Oklahoma State University, 1981-1984.

Professional and Honorary Societies: Member of the Bangladesh Institute of Engineers; Member of the Bangladesh Society of Agricultural Engineers; Member of the Indian Society of Agricultural Engineers; Member of Alpha Epsilon; Student Member of the American Society of Agricultural Engineers; Student Member of the Oklahoma Society of Professional Engineers and the National Society of Professional Engineers.

Awards